CRANFIELD UNIVERSITY

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A GUN BASED TEST METHOD TO SIMULATE MINE BLAST AGAINST BOOTS

CRANFIELD DEFENCE AND SECURITY

PhD thesis

Academic Year: 2016

Supervisor: Professor Ian Horsfall

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ABSTRACT

Blast mines have played a major role in almost every conflict from the two world wars to the most recent skirmishes. They provide a psychological threat in addition to denying access to areas and exerting a huge toll on the logistic and medical capabilities in conflict zones. Due to the lack of inexpensive and reliable mechanical technique that would work consistently and without the danger of mines being missed, human deminers are often preferred. This means that deminers are under constant threat of serious traumatic injuries to lower extremities, potentially leading to amputation and death.

A limited number of studies have been published in the open literature regarding the performance of boots both commercially available and those that are specifically designed to deal with anti – personnel mines. The issue with these studies is that while they have followed a common test method, they have been unable to agree on the variables involved. This has resulted in studies that produce vastly different results making them difficult to compare. However, while all of them have concluded that none of the commercial boots tested provided adequate protection against even a small mine, there have been varied results observed with respect to certain mine resistant boots with some reporting adequate protection while others reporting outright failure. Blast testing involves a large number of variables making it difficult to produce repeatable, consistent and conclusive results, and therefore difficult to prove the claims of different boots.

The aim of the research project was i) to investigate the reliability and reproducibility of current blast test methods while testing the performance of commercially available boots and ii) to develop a new test method that is able to replicate the performance of blast test methods that is capable of producing more consistent and reproducible results while being cheaper, quicker and flexible.

To address these challenges, blast testing was conducted using a variety of commercially available boots – i) to test their performance and if the results observed line up with the literature and ii) to obtain baseline data for further analysis. Blast testing demonstrated that none of the commercially available boots offer adequate protection even against a small mine. They additionally highlighted issues with this type of testing regarding their accuracy and repeatability. This was compared to an analysis of the effect that foams have on reducing loads, which showed that by increasing the number of layers it was possible to reduce the loads measured. However, the total impulse measured remained the same irrespective of the foam thickness. The baseline data from the blast test was used to develop a new gun based test in order to address the limitation observed during blast testing. The final version of this test was able to match the performance of the blast test while being able to produce penetration. A subsection of the research tested the effectiveness of socks as a means of preventing contamination. Two different types of socks were used in three different arrangements and testing revealed that socks have a positive effect on preventing contamination.

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NOMENCLATURE

General glossary

Bloom (gel strength/jelly strength)	It is a test to measure the strength of gelatine and indicates the force required to depress a prescribed area of the surface of 6.67% gelatine gel at 10^{o}C to a distance of 4mm (Rousselot, 2014).
Deminers	Personnel involved in the task of demining.
Demining	“To remove mines and especially unexploded mines from an area” (Merriam – Webster Dictionary, 2014).
Explosive charge	Weight of explosive material being used.
Gelatine	“a clear substance that is made by boiling animal bones or tissues: a colloidal protein composed of collagen” (Pearsall, 1999, p. 588).
Impedance	“A measure of the opposition of a system to the acoustic flow as a result of an acoustic pressure applied to it (Kinsler, 1999).
Overburden/depth of burial	The depth at which the mines are buried.
Para – aramid	Synthetic fibres that are used in aerospace and military applications for ballistic protection.
Penetrating	“Having the power of entering, piercing or pervading” (Merriam – Webster Dictionary, 2014).
Penetration	“The act or an instance of penetrating” (Merriam – Webster Dictionary, 2014).
Permanent cavity	“Void left after temporary cavity has collapsed following initial penetration” (Janzon *et al*, 1997).
Shank	A supportive structure in the boots cast into the sole made of rigid materials such as steel, fiberglass or Kevlar. It provides support to the heel and calf and protects it from penetrative injuries.
Shear	“A straining action where applied forces produce a sliding or skewing type of deformations. A shearing force acts parallel to a plane as distinguished from tensile or compressive forces which act normal to a plane” (McGraw – Hill, 2003).
Shock wave	“A very narrow region of high pressure and temperature formed due to the rapidly expanding detonation products as a result of detonation of

an explosive charge” (Martin, 2010, p. 747).

Temporary cavity The space that is temporarily created as the projectile pushes the medium ahead of due to high pressures created around the projectile. (Janzon, 1997, p. 27).

Torsion “The twisting or wrenching of a body by the exertion of forces tending to turn one end or part about a longitudinal axis while the other is held fast or turned in the opposite direction” (Merriam – Webster Dictionary, 2014).

Medical glossary

Amputation	"To cut off part of a person's body" (Merriam – Webster Dictionary, 2014).
Bilateral	"of, relating to, or affecting the right and left sides of the body or the right and left members of paired organs" (Merriam – Webster Dictionary, 2014).
Contaminate	"to make something dangerous, dirty, or impure by adding something harmful or undesirable to it" (Merriam – Webster Dictionary, 2014).
Debridement	"The surgical removal of lacerated, devitalized or contaminated tissue" (Merriam – Webster Dictionary, 2014).
Demyelination	The loss of the insulating myelin sheath covering the nerves.
Fanning	"To spread out like a fan" (Merriam – Webster Dictionary, 2014).
Prosthesis	"An artificial device that replaces a missing or injured part of the body" (Merriam – Webster Dictionary, 2014).
Sepsis	"illness caused by an infection in a part of the body resulting from the spread of bacteria or other toxins from a focus of infection" (Martin, 2015).
Shear	"an applied force that tends to cause an opposite but parallel sliding motion of the planes of an object. Such motion causes tissues and blood vessels to move in such a way that blood flow may be interrupted" (Miller – Keane, 2006).
Trans – femoral amputation	"Amputation of the leg across the femur often referred to as above knee amputation" (Smith, 2003).
Trans – tibial amputation	"Amputation of the leg across the tibia often referred to as below knee amputation" (Smith, 2003).

Abbreviations

ALT	Altberg MKII
ANOVA	analysis of variance
AP	anti – personnel mines
BCB	British Combat Boot/Assault boot
BDL	boot damage level
CCMAT	Canadian Centre of Mine Action Technologies
CLL	Canadian Lower Leg
CT	computed tomography
DWB	Dunlop Wellington Boot
FSL	Frangible surrogate legs
HDP	Humanitarian Demining Program
ICBL	International Committee to Ban Landmines
LDE	Lowa Desert Elite
LEAP	Lower Extremity Assessment Program
MGI	microbial growth inhibitor
MTS	mine trauma score
NATO	North Atlantic Treaty Organisation
PU	polyurethane

TCL	total crack length
U. S.	United States
UHMWPE	ultra – high molecular weight polyethylene
UN	United Nations

Variables and constants

A	cross – sectional area, m^2
D	burial depth to the centre of the mine, m
E	energy in explosive charge, J
F	force, N
I	impulse, N.s
I_{max}	maximum impulse of blast, N.s
KE	kinetic energy, J
M	mass, kg
V	velocity, m/s
Z	standoff distance of the target to the centre of the mine, m
P	density, kg/m^3

Chapter 1: INTRODUCTION

Since their inception during the U.S. Civil War (Physicians for Human rights, 1993), blast mines have played a major role in almost every armed conflict from the two World Wars to the most recent skirmishes. The widespread use of tanks during World War I led to the development of anti – tank mines, however due to the simplistic nature of the earlier designs these were easy to counter and redeploy by opposing forces. Due to this, between the two World Wars a considerable amount of resources was dedicated into developing anti – personnel mines as a deterrent to protect anti – tank mines and prevent their removal. Due to the ease of producing them and the physical and psychological threat that they posed, the use of anti – personnel mines gained widespread use in the following years as a deterrent to access to areas. This has resulted in a major effect on civilian casualties, severely increasing their numbers which is a shift from previous conflicts where the majority of the casualties were military personnel. Anti – personnel mines were not designed for this purpose, but it is a consequence of their effectiveness.

Being economical to produce, anti – personnel mines have become a major equaliser during conflicts in third world countries. Since their inception mines have become more sophisticated, with different types and variations in existence, making detection and removal much more complicated. After World War II a new trend emerged, wherein mines were indiscriminately scattered during conflicts by opposing forces. These have accounted for more injuries than any other armament due to a lack records of where and how many of them were deployed (Muschek et al, 1998).

Although the 1997 Convention on the Prohibition of the Use, Stockpiling, Production and Transfer of Anti – Personnel Mines and their Destruction has gone a long way towards the eradication of antipersonnel mines both locally and internationally, it has only 162 signatory states out of 196 countries. The Landmine Monitor Report 2015 (Landmine Monitor Report, 2015) states that non signatory governments of the convention have been found to use antipersonnel landmines between October 2014 and October 2015. In addition, non – government armed groups in 10 countries such as Afghanistan, Iraq, etc. have been using antipersonnel mines or victim activated explosive devices acting as anti – personnel in the same period.

The number of global causalities caused by landmines which include anti – personnel mines rose by 12% in 2014 compared to 2013 with 3,678 casualties recorded in 2014

(Landmine Monitor Report, 2015). This is due to the improved methods of tracking casualty events as the year's progress rather than an increase in actual events. This highlights that landmines are still a major issue. Civilians accounted for 80% of the casualties recorded, highlighting the need for a simpler solution that can be used to deal with landmines, rather than using expensive and complicated systems.

Mines provide both a psychological and logistical advantage. Forces attempting to breach mines field have to be tactful in their approach resulting in a loss of speed and mobility on the battlefield as well as using critical assets to clear safe paths, hence posing a serious stress on the logistic and medical capabilities on the advancing forces. This puts severe stress on the emergency services of many countries and even with international assistance they are quickly overwhelmed, leading to an increase in the morbidity and mortality rates (Landmine Monitor Report, 2015). In addition, landmines have a lasting effect on the daily lives of the indigenous population of the countries where they have been widely proliferated without any record of where, when and which mines have been placed. This limits access to areas that would otherwise be used for agricultural purpose, forcing the native population to either abandon the area leading to increased risks of famine or forcing them to farm in mined areas, thus increasing the number of victims.

At present there is not an inexpensive and reliable mechanical technique for removing antipersonnel mines that works in all terrains; mechanical means of removing mines are restricted to those areas which are relatively flat. Hence, to ensure that the mines are removed safely and thoroughly; thereby ensuring the safety of the native population, human deminers will have to be used until novel techniques are developed that provide the guarantee of reliable and safe removal. Individuals involved in anti – personnel demining efforts are under serious threat of traumatic injury to lower extremities often resulting in amputation or death. Hence, protective equipment worn must have an adequate balance between protection and mobility to be useful in the field. This means that it is necessary to develop an understanding of the types of injuries produced by the blast and arrive at a solution that strikes a balance between optimum protection and surgical outcome.

As the literature review will demonstrate, a considerable amount of work has been done looking at the effectiveness of different anti – personnel mine boots in order to develop one that works well. While a few of the boots work adequately (Bergeron et al, 2007), they have quite a few limitations. Conventional mine boots rely on design strategies such as a large standoff or a wedge shaped sole to achieve a level of protection, which means that they lack the ergonomics to be worn continuously in theatres where the majority of the ground is uneven. This may result in sprained and broken ankles before the anti – personnel mines are even encountered and if the ground is even it would make much more sense to use a mine clearance vehicle as the threat is considerably less. Hence, a more optimal solution is needed that would strike a balance between the burden of wearing a specific anti – personnel mine boot continuously on one hand and not having adequate protection when a mine is not expected on the other. The solution would be to use boots already available on the market that would be able to mitigate the blast to a certain degree and produce a surgical outcome that is a lot better than the scenario where adequate protection hasn't been worn.

While the performance of anti – personnel mine boots has been thoroughly tested in the literature (Lans, 1999; Harris et al, 2000; Bergeron et al, 2006; Van der Horst et al, 2008), very little research has been done looking at other forms of protection that can be worn in addition to the boots in order to increase the overall level of protection. This can either be in the form of protective equipment worn over trousers or protective layers incorporated in the boots themselves that are composed of para – aramids like Kevlar®[1] or Ultra high molecular weight polyethylene (UHMWPE) like Dyneema®[2]. These fabrics would provide protection against a mine by providing fragment protection.

Testing the blast performance of boots and socks requires conducting blast tests. The literature (NATO TR – HFM – 089, 2004) demonstrates that this is a very time consuming and complex process involving a large number of variable which change from study to study. This has resulted in all of the literature studies having a limited number of repeats making it difficult to compare the results between the different studies where a minor change in any variable produces drastically different results. Hence, a new method is required that is able to replicate the physics of conducting blast test but at a fraction of the cost and producing more reproducible results in a shorter time period. This is supported by the need of the boot manufacturing industry to develop more robust methods to test anti – personnel mine boots.

1.1 Aim and outline of the study

The aim of the research presented in this PhD thesis was to develop a new methodology that was able to overcome the limitations of the blast tests and that was able to

[1] Para-aramid synthetic fibre developed in 1965 at DuPont.
[2] Ultra-high molecular weight polyethylene fibres used armour

meet its performance in terms of the total impulse and impulse per unit area, while producing more reliable and reproducible results. This necessitated a small scale study of the loading mechanisms produced by small mines on commercially available boots to obtain baseline data for comparison and characterising the threat by determining if these boots are able to offer protection similar to that offered by dedicated systems specifically developed for this purpose; damage caused by the blast was evaluated in terms of the loads measured and the boot damage. The final objective was to test how the protection offered could be altered by using simple solutions such as increasing the thickness of the sole and how using socks can affect the contamination by environmental debris, and therefore the medical outcome.

1.2 Structure of the thesis

After setting the foundation for this research in chapter one; chapter two is a literature review of the topics that are relevant to this thesis, namely; statistics of antipersonnel landmine injuries, landmines, blast physics and propagation, types of available demining footwear and the mechanisms involved, injury mechanism in landmine blast, previous work on blast mines and protection offered by boots, problems with the current test method, gelatine as a tissue simulant and finally cellular materials and work done on foams.

Chapter three looks at the effect that foams have on the loads measured while, chapter four evaluates the performance of boots using blast tests similar to previous work done in the literature and highlights the issue with current test methodology.

Chapter five is dedicated towards developing a new gun based test method to simulate blast tests that is able to overcome the issues of reliability and reproducibility associated with it, while matching its performance in terms of total impulse and impulse per unit area.

Chapter six looks at the protection offered by socks and if they are able to affect the outcome in terms of penetration depth by the environmental debris, while chapter. Chapter seven brings together and discusses the results of the previous four chapters. This is followed by the presentation of the conclusions and suggestions for further work.

Chapter 2: LITERATURE REVIEW

2.1 Statistics

There has been a slow change in the perception of landmines. Once considered a tactical military weapon, they now pose a greater threat to civilians than military personnel, and hence a major humanitarian concern. The International Committee to Ban Landmines (ICBL) has sought to ban Landmines culminating in the Ottawa Treaty of 1997, a number of countries have yet to accept it. A report published by them in 1999 estimates that the current number of buried landmines worldwide ranges from 60 to 110 million. As of 1998, it was estimated that landmines kill about 800 people per month and injure an additional 1200, amounting to 24,000 new victims per year. Since these statistics are only compiled by certain medical facilities, a large number of these incidents go unrecorded, resulting in figures that are quite conservative. With about 5 to 10 million anti – personnel mines being produced annually and 100 million already in stockpiles ready for use; anti – personnel mines will continue to be a significant threat for years to come (Landmine Monitor Report, 2015).

A report on the analysis of landmine injuries of 757 victims by International Committee of the Red Cross classified the injuries into three types. Pattern 1 injuries occur when a buried mine is stepped upon and produce severe lower limb injuries including traumatic amputations and genital injuries. Pattern 2 injuries occur when the mine explodes near the victim. This may be due to a buried mine activated by another individual or a mine triggered by a trip wire. Lower limb injuries occur but are less severe with traumatic amputations less common. Injuries to the head, leg and abdomen are common in this type of injury (Coupland et al, 1991). Pattern 3 injuries occur when the device explodes whilst the victim is handling it. Since the purpose of the PhD is to evaluate the lower limb injuries as a consequence of stepping directly on a buried mine, pattern 1 injuries are the most relevant and will be the primary focus.

A survey published by the United States Department of Defence on accidents occurred during demining operations as part of their Humanitarian Demining Program (HDP) (Carruthers et al, 1999) revealed that ammunitions including anti – personnel mines, anti – tank mines, grenades and mortars resulted in 232 accidents resulting in 295 victims. 79% of these accidents were attributed to anti – personnel mines accounting for 78% of the injured people and 81% of the fatalities. Of the cases involving anti – personnel mines, 83% of the accidents were with blast mines as opposed to fragmentation mines. In addition, it was noted that although blast mines were attributed as the cause of the majority of the accidents this resulted in only 7% of the fatalities, while 38% of the fatalities were caused by anti – personnel fragmentation mines, nearly 6 times more than blast mines. Although both fragmentation and blast mines are a major hazard, the above data clearly demonstrates that, there is a greater risk of encountering blast mines, but the threat is lower due to the fact that blast mines have a smaller range and cause most of the damage to the person in the immediate vicinity while fragmentation mines have a larger area and are able to cause multiple casualties. However, fragmentation although posing a smaller risk, poses a greater threat since the risk of getting severely injured is much higher.

Excavation of mines accounted for 34% of the injuries while 37% were caused by missed mines (Carruthers et al, 1999). In addition, missed mines resulted in 3.5 times more leg injuries than excavated mines indicating that the person was standing at the time of the accident. Up until 1998 it was estimated that for every 100,000 mines removed per year another 2 million were being laid down (Heffernan, 2003). However, if no newer mines were laid down it was estimated that it would take approximately 1,100 years to remove the existing ones. It was estimated that the cost to remove a mine was 50 times that of the cost to buy them. In 1996 the UN Secretary General increased the estimate to remove all the mines from $33 billion to $50 billion (Physicians for Human Rights, 1993) assuming no new mines were laid henceforth. In addition, for every 5000 mines removed one deminer was killed and another 2 were injured. This creates a severe drain on the available resources in a country since surgical care and fitting of an orthopaedic appliance would cost $3000 per amputee in developing countries. This means for the 250,000 amputees estimated worldwide by the UN it is a bill of approximately $750 million. This clearly demonstrates that developing adequate protection for lower limbs is a worthwhile goal (Land Mine Monitor Report, 2015).

2.2 Landmines

Landmines are explosive devices that contain varying amount of explosive charges that are designed to disable or destroy enemy targets passing near or over them by being concealed above or below the ground. Though different detonation mechanisms are possible such as pressure plates, trip wires or tilt rods, they are typically detonated by either driving on top of the mine or stepping on it. The pressure of a vehicle driving over a mine or someone stepping on it drives the firing pin below the pressure plate into the pressure fuse and detonates the detonator. This leads to the detonation of the main charge and leads to the eventual explosion. This leads to a detonation wave that propagates through the mine, generating high pressures and temperatures in the detonation products. The detonation product expands rapidly and push the soil and air in the immediate vicinity of the blast away from it. Due to the expanding detonation product the soil moves upwards and gains kinetic energy and allows the detonation products to break through. Damage is primarily caused as a consequence of the blast wave produced or fragments from both the mine or the environment. Over the years mines have undergone rapid development, becoming more effective and impactful, and becoming specialised with respect to the intended target and the subsequent damage that can be caused. This specialisation has led to their classification into two types – anti – vehicle and anti – personnel mines (Physicians for Human rights, 1993). For the purpose of this PhD thesis only anti – personnel mines will be considered since they are the primary threat to military and civilian populations.

2.2.1 Anti – personnel mines

Designed as a means to prevent access to anti – tank mines, anti – personnel mines over years of development has evolved into an ideal weapon. They are designed to rapidly incapacitate a target which could either be humanitarian deminers or military personnel, by severely maiming or killing them, thereby increasing the logistical support burden on the opposing force. Anti – personnel mines are classified into two types.

2.2.1.1 Blast mines

These devices typically comprise 50 to 500g of high explosive that is contained in a plastic or metal shell (figure 2.1). For example, the PMA – 2 mines contain 100g of TNT explosive, PMA – 3 mines contain 33g of Tetryl and VS – 50 mines contain 43g of RDX. They are designed to be concealed in the ground, buried to a depth of several centimetres and containing minimal amount of metal making them difficult to detect and are usually triggered when the victim steps on them. They are designed to by very efficient, by causing rapid incapacitation whilst using the smallest amount of charge needed. They result in severe muscular and skeletal damage due to the direct effect of blast on the human tissue. Additionally, there is a degree of fragmentation injury involved due to the breakdown of the mine components as well as the soil and other debris being propelled by the blast (Banks, 1997) which when combined with the muscular and skeletal damage usually necessitates amputation.

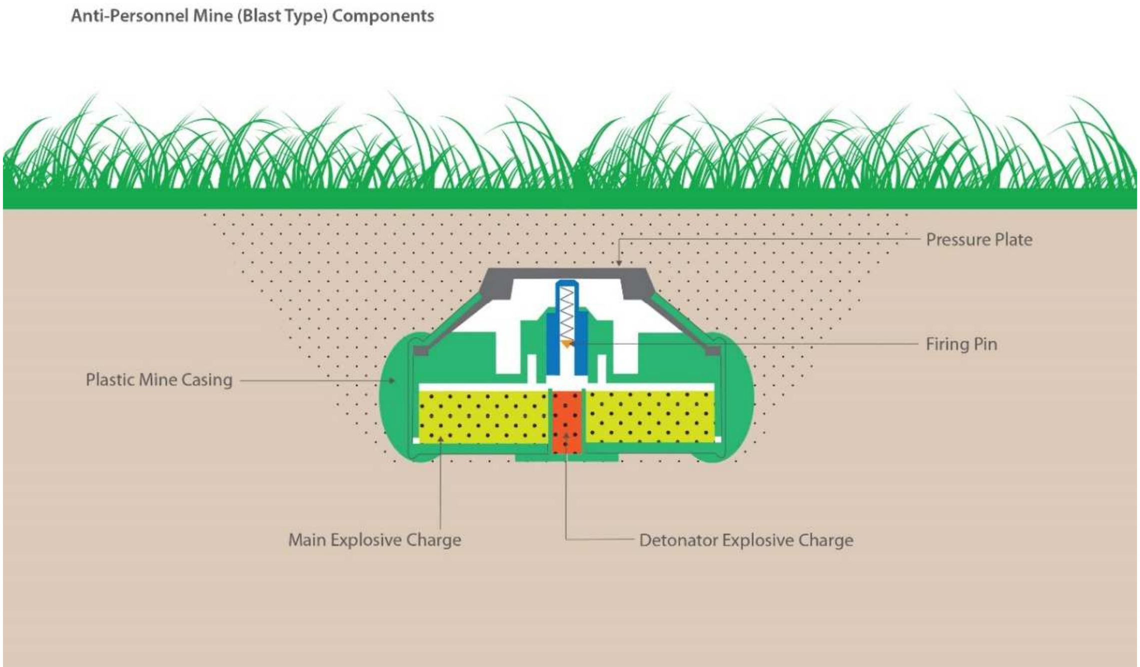


Figure 2.1: Anti – personnel blast mines

2.2.1.2 Fragmentation mines

Unlike blast mines fragmentation mines are designed to cause injury to a larger number of personnel. They are designed to explosively disperse fragments at high velocities up to several meters away causing shrapnel wounds to nearby personnel. While blast mines are generally small, containing minimal amounts of metal, fragmentation mines are larger containing metal components making them easier to detect. They have a lethal range of 15 – 25 metres, though they can be dangerous up to 100 metres (King, 1998).

2.3 Blast physics and propagation

When the fuse is triggered a large amount of energy is released due to the detonation of an explosive material which is accompanied by a highly pressurised volume of hot gases that expand rapidly. This mass of hot high pressure gas is called the detonation product. It is estimated that this detonation production produces pressures up to 0.3 MPa and a temperature of about 3000 – 4000^{o}C (Ngo et al, 2007). The rapidly expanding gases force the air surrounding the charge out of the space it previously occupied causing it to become highly pressurised. This leads to a blast wave (figure 2.2) which consists of an instantaneous rise in pressure over and above normal atmospheric pressure and this is called the blast overpressure that rapidly dissipates over a very short duration. The maximum pressure that is measured during the blast event is called the peak overpressure. As the energy of the expanding gases dissipates, the pressure of the blast wave falls and undergoes rarefaction which leads to a negative pressure phase due to air that was previously vacated. This is quickly normalised by the air that moves in from the surrounding (Bailey et al, 1989; Smith and Hetherington, 1994). The objects in the immediate vicinity of the blast undergo a change in momentum due to the forces acting on it, which is quantified by impulse which is the integral of the force with respect to time or alternatively it is the area under the force time curve (Serway, R.A. and Jewett, J.W., 2013).

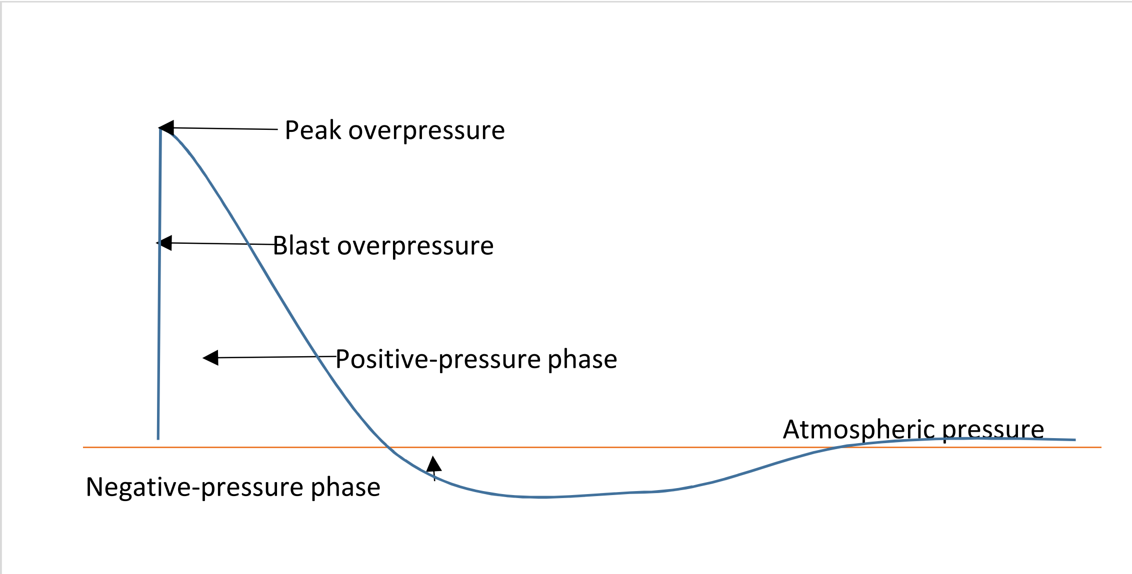


Figure 2.2: Blast pressure – time curve

Since landmines are usually buried under soil the interaction with the soil plays an important role in the output from a mine (Hlady, 2004; Fiserova, 2006). When a buried charge detonates, the blast wave propagates through the explosive material and produces detonation products having high pressures and temperatures. The hot gas pushes on the surrounding soil compressing and displacing it from the centre of the explosion. Since, the soil below the mine is densely packed, it offers much more resistance than air. Hence, the hot gases take the path of least resistance and the explosion is directed upwards, displacing the soil above at high velocities called soil ejecta (Bergeron et al, 1998; Fiserova, 2006; Ramasamy, 2009). At the point of detonation, soil and air in the immediate vicinity are rapidly dispersed by the expanding gases of the blast resulting in an increase in pressure, producing a blast wave (Bailey et al, 1989). The soil that is displaced, allows the detonation products to break through the surface imparting kinetic energy to the soil. However, the difference in impedance between the soil and the air means that the blast wave is mostly reflected back into the soil (Tremblay et al, 1998). This results in the soil absorbing most of the blast wave, hence the blast overpressure will be lower than if the blast took place in air. If the target is in contact with the soil however, energy would be transmitted to it by the soil and would undergo a change in momentum which can be quantified by impulse. Where the total impulse is defined as the integral of a force over the time interval for which it acts which is the area under a force time curve (Serway, R.A. and Jewett, J.W., 2013). Injuries to people in the immediate vicinity is caused by the objects and other environmental debris that are propelled by the blast wind (Stuhmiller et al, 1991). Hence, for a buried charge the blast overpressure is largely eliminated and most of the damage is done by the impulse imparted by the soil which is focused on a smaller area.

Peak over pressure, duration and the likelihood of injury can be influenced by several factors such as the medium in which the blast occurs, the distance of the target from the explosions and distance of the target from solid surfaces (Stuhmiller et al, 1991). The first is the medium in which the explosion occurs and the depth of the overburden. Blast waves propagate more rapidly in mediums that are incompressible. Since solids and liquids are largely incompressible, the blast wave propagates rapidly with a slower rate of dissipation than when it occurs in air. Hence, overburden decreases the expansion rate of the detonation products considerably. Secondly is the distance from the point of explosion (Phillips, 1986). The blast energy decreases as the blast wave decreases and the blast overpressure decreases in a manner that is inversely proportional to the cube of the distance from the point of explosion as defined by Hopkinson – Cranz scaling laws (Hopkinson, 1915; Cranz, 1916). Thus if the distance from the point of explosion is doubled the blast overpressure experienced will be one eighth of the original value. Despite the fact that the pressure drops rapidly over a short duration the magnitude of the pressure in the immediate vicinity of the blast is extremely high and would cause significant damage (Bailey et al, 1989). For a 100g mine blast at 100mm the pressure ranges from 600 – 12,00MPa. This would drop to 36 – 73MPa at 200mm. However, most materials including human tissues cannot withstand such extreme pressures and simply break down. This is true even for the materials used in the construction of regular footwear. The third factor is the amplification of the blast overpressure and the force experienced as a result of its reflection from solid surfaces. Therefore, people closer to a wall will experience a greater blast overpressure and will be at a risk of significant greater injury (Wolf et al, 2009).

2.3.1 Calculating the total impulse of the blast

One method of quantifying the blast is by calculating its total impulse. Since impulse is the product of mass and velocity impacting a target, Westine (Westine et al, 1985) defines the impulse from a land mine explosion impacting a target as a result of the soil ejecta travelling at very high velocities. The loading generated from the impulse is characterised by a high pressure during a short period of time. The duration is very short so the exact shape of the pressure time loading is not very important (Smith and Hetherington, 1994).

Tremblay (1998) defines the total impulse for a particular standoff distance for a horizontal deflector using the following equation:

$$I = \left(\frac{0.5857}{\varsigma^2}\right)\left(1 + \frac{7D}{9Z}\right)\sqrt{\frac{\mathrm{PE}}{\mathrm{Z}}} \qquad \text{… equation (1)}$$

Where,

$$\varsigma = \frac{D}{\left(Z^{\frac{5}{4}}\right)\left(A^{\frac{3}{8}}\right)\left(\tanh\left(\frac{2.2D}{Z}\right)^{\frac{3}{2}}\right)} \qquad \text{… equation (2)}$$

Where,

D = burial depth to the centre of the mine [m]

Z = standoff distance of the target to the centre of the mine [m]

P = soil density [kg/m3]

E = energy release in explosive charge [J]

A = cross sectional area of the mine [m^2]

From the equation it can be seen that the total impulse is related to the charge weight, the burial depth and inversely related to the standoff distance. This means that as the charge weight increases the energy from the blast will increase as well, thereby increasing the total impulse. While the equation shows that as the burial depth increases the total impulse will increase due to the blast and sand being focused vertically, this is not applicable beyond a certain burial depth as shown by Hlady (2004). This is because this is an empirical equation and is valid over only a limited range. Standoff distance is inversely related to the burial depth, therefore as the standoff distance increases the total impulse will drop rapidly since the blast and the sand will not be able to transfer the energy to the target before it dissipates.

2.4 Different anti – personnel mine boot designs and the mechanism of protection

Since a target in contact with the soil undergoes a change in momentum during the blast event, it has an impulse acting on it due to the energy of the soil that is impacting. Hence, it is necessary to reduce the magnitude of the energy transferred in order to minimize the likelihood of injury.

Fujinaka et al. (1966) looked into the mechanics that were employed in blast protective boots at the time. The paper identified the problem that for a boot to be useful, it should have an adequate amount of mobility. This however poses serious limitations on the weight, design and dimensions of the boot. The paper identified three parameters which characterize the impulse load generated by the land mine – the peak pressure, the peak impulse per unit area, and the total impulse.

The paper (Fujinaka et al, 1966) identified that the only possible method to reduce the total impulse was to adequately shape the sole. Based on a number of experiments it was determined that a simple wedge shaped sole at an angle of 112 degrees would be able to reduce the total impulse by as much as 36%. When this was compared to regular flat bottomed steel surface it was found that the amount of total impulse received by the flat bottomed surface at a distance of 1 inch from the point of explosion was comparable to the wedge shaped outsole in contact with the mine. In addition, the use of a wedge shaped outsole allowed the possibility to use different configuration of materials in the wedge.

As explained previously when the foot is in contact with the soil impulse is imparted to it and it undergoes a change in momentum. The impulse acting on the foot is defined as the integral of force with respect to time. Since momentum is the product of mass and velocity, when the momentum of a body changes, either its mass or velocity will change. Since in a blast test the mass of the foot will remain the same, the foot undergoes a change in velocity and is accelerated. The impulse per unit of area input to the foot is not uniform over the entire surface of the boot. Fujinaka et al. (1966) identified total impulse and the impulse per unit area as the two important factors that determine the protection offered by the boot. It was identified that the most effective way to reduce the impulse per unit area was to use a protective shank, which is a piece of material that is cast into the sole. The shank can be either metal or plastic and it was found that a shank that was as long and wide as practical was needed to give an area as large as possible.

If the given impulse per unit area was fixed, the damage to a given structure could be minimized by reducing the peak pressure. This is generally done by increasing the time duration of the pressure pulse. The paper looked at M – 14 mines, which produced a peak pressure of 40.4 kilo bars (4095MPa) in the plastic surface of the land mine. In the case of a flat sole surface containing a high impedance material such as aluminium this value increases up to 71 kilo bars resulting in higher damage. The peak pressure that a human cadaver leg can tolerate before amputation has found to be about 20MPa. Hence, the peak pressure has to be reduced by at least two orders of magnitude before any hope of salvaging the limb can be realised. The paper identified that a layered system of materials can reduce the initials peak pressure by two orders of magnitude. A honeycombed aluminium structure in a single layer with a crushing strength of 29MPa can theoretically reduce the peak pressure to 27MPa. This assumes that the structure can be treated as a low impedance material with high propagation velocity and low gross density. When this is coupled with materials of different impedance it was found that it was theoretically possible to reduce the peak pressure to salvageable limits.

Based on these findings (Fujinaka et al, 1966) a number of concepts were designed and tested using a wedged shaped outsole with some form of lateral support to maintain stability, a shank of relatively large area and the use of impedance mismatch techniques couple with crushable materials. Testing was done using mines of 450g charge. Of all the concepts, the one containing double layered honeycombed structure with a steel shank in between enclosed in a wedge shaped outsole and a steel protective cup were found to be the most effective.

Fujinaka and Mac Donald identified that the standard boots are not effective in preventing amputation of a foot exposed to a small anti – personnel mine. The paper dealt with developing a supplementary system to be used in conjugation with previously developed combat boots. The concepts were designed, both using solid aluminium shanks that were directly moulded into urethane casting and were attached to commercially available over boots by means of neoprene rubber that were adhesively bonded together. The paper showed that it was possible to reduce the loads measured by 90% when an over boot with aluminium sabot are used in conjugation with the protective boot (Fujinaka et al, 1966).

The work done by Muschek et al. (1997) proved the previous work of Fujinaka et al. (1966). Muschek performed an analysis of the mechanical and chemical properties of the different components used in boots. The paper looked at how varying the materials and thickness of the components used in boots affects their effectiveness. The paper collected the mechanical properties of the different components used in boots and input them into a finite element analysis model to determine how the boots response changes with changes to blast overpressure. Using the same finite element model, the material properties and dimensions were changed to determine the most optimum design. The results were similar to previous work done by Fujinaka et al. (1966). It was seen that the pressure from the blast is immediately enough to cause major deformation of all components of the boot. As the blast progresses the rubber is completely compressed and the aluminium honeycomb begins to completely collapse which causes high stress above the Kevlar in the sole of the feet. It was found that although the boots offer a reduction in the force, due to the large number of variations in the biomechanical properties of bones from person to person, variations in the forces experienced can be as high as two orders of magnitude. The paper made a number of observations on the effect that different material combinations had on the effectiveness of the boots. It was observed that the easiest method for force reduction was by increasing the base and top thickness which results in a proportional reduction of the total impulse. In addition, it was observed that this was true for steel but not for aluminium, however when the top and bottom were varied with foam it was found that aluminium as the top material produced a lower force that steel of the same thickness (Muschek et al, 1997).

Hence, the design philosophy of anti – personnel mine boots is based on three strategies – Standoff, Attenuation and Deflection.

Standoff is the distance of the sole of the foot from the point of explosion. Increasing the standoff distance has been found to be the most effective in reducing the loads measured wherein increasing the standoff distance by as much as 50% decreases the energy transferred by up to 60% (Mah et al, 2007). Using frangible surrogate legs as the surrogate, Mah et al. (2007) looked at the effect that different standoff distances have on lower limb injuries from anti – personnel blast mines. It was found that the greater the standoff the less severe the injury. This can be explained by the previous literature where it can be seen that the blast pressure reduces significantly when the distance from the point of explosion is doubled (Phillips, 1986). Ex: Med Engineering Spider Boots (figure 2.3), Owen Mills™ inflatable minefield safety shoes (figure 2.4).

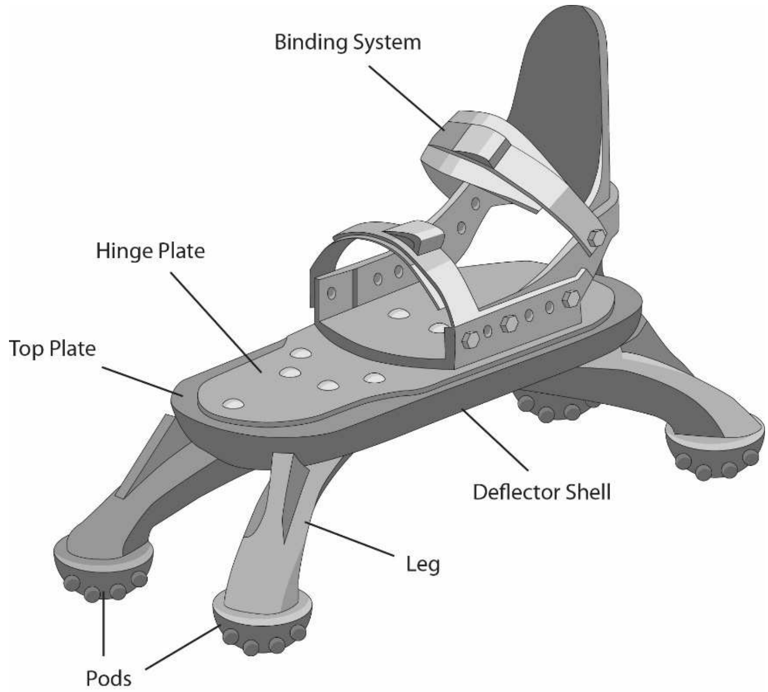


Figure 2.3: Med – Eng[1] Spider boots

Figure 2.4: Owen Mills™ [2]inflatable minefield safety shoes (Owen Mills Inc., 2016)

While both of these systems provide a standoff from the mine, they do so at the expense of mobility and dexterity which combined with the uneven ground would make it difficult to move rapidly. However, one major advantage of these boots is that in the case of the spider boots the boot leg that would make contact with the mine is offset and it is unlikely that the mine would detonate directly under the heel. In the case of the inflatable shoes, the contact area is increased which has the same effect of the spider boots of detonating the mine

[1] Med-Eng, Ontario, Canada
[2] Owen Mills Company, Van Nuys, United States

away from the foot. whether the standoff consisted of an air gap or Styrofoam spacer. The work done by Mah et al. (2007) agreed with the work done by Bass et al. (2004) and Van der Horst et al. (2008) that boot damage was not an accurate predictor of lower limb injury. This was because the boots tested by Mah et al. showed no external signs of damage due to the standoff distance despite the high loads measured.

However, an important factor to note is that the protection based on standoff is dependent on the medium filling it. Mah et al. (2007) showed that the protection varies when the standoff medium changes from air to foam, with greater standoff distance needed for foam since the blast wave dissipates more slowly over the same distance. To achieve the same level of protection, the paper showed that it was only required to have a 150mm air standoff, which increased to 200mm for Styrofoam.

Attenuation is based on designing boots using materials whose physical properties are altered during the explosive event, thus utilizing a portion of the energy from the blast and reducing the energy transferred (Van der Horst et al, 2008). e.g.: Aluminium honeycomb (figure 2.5), are structures used in boot soles that undergoes spalling when exposed to blast wave (figure 2.6).

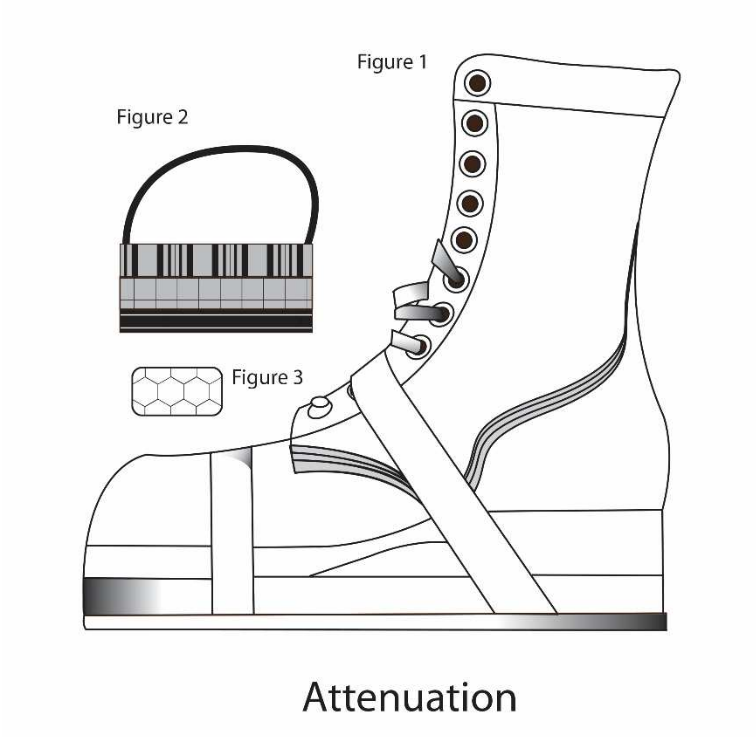


Figure 2.5: Honeycombed structure used in boots

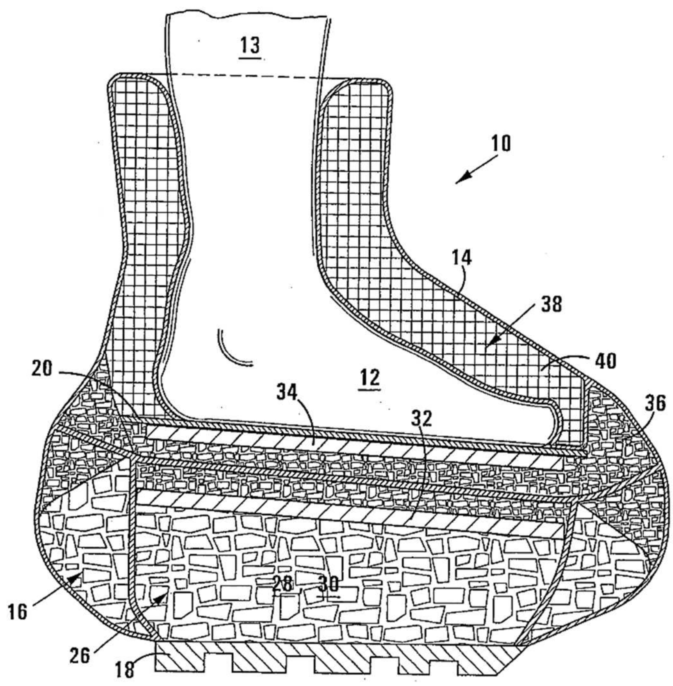


Figure 2.6: Sole composed of material that spalls due to shockwave (Protective footwear US Patent no. US20060000117 A1)

The last strategy is deflection where an angled plate or angled design of the sole is used to deflect a portion of the blast energy away from the foot (figure 2.7). However, a major problem with this is that in real world application the plate orientation varies depending on the position of the foot relative to the mine and may increase the transmission rather than decrease. Genson (2006) showed that angle of the plate has a significant effect on the total impulse from a buried charge, however this is dependent on both the depth of burial and the standoff distance, which lines up with the observations made by Fujinaka et al. (1966). He concluded that plate angle is inversely proportional to the standoff distance with respect to the effect on total impulse and directly proportional to the burial depth. This means that there is an optimum standoff distance at which the shape of the plate has an effect on the total impulse beyond which it has little effect. The angled plates are more effective at closer standoff distances and as the depth of burial increases the angle of the plate must be larger to deflect the soil ejecta and reduce the total impulse (Genson, 2006) (figure 2.8). In addition, in those cases where a wedged shaped sole is used, it makes it very difficult to walk and in most cases leads to sprained ankles. Furthermore, the use of the plate increases the danger of causing far greater damage due to the possibility that the plate would be accelerated at great velocities (Fujinaka et al, 1966).

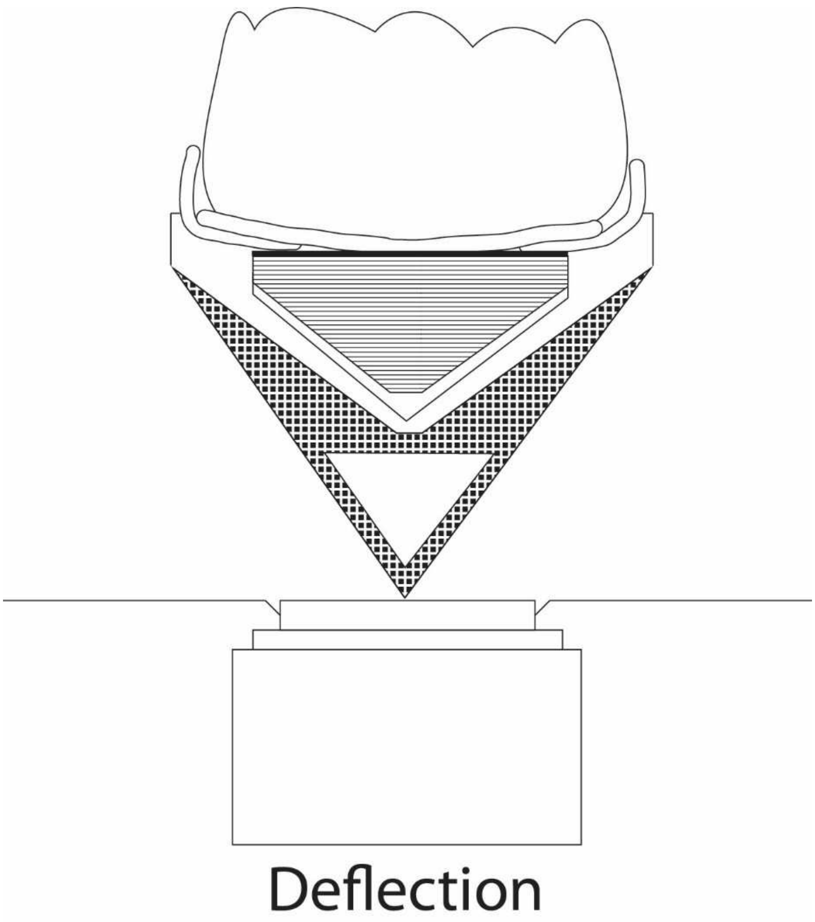


Figure 2.7: Wedge shaped sole demonstrating deflection

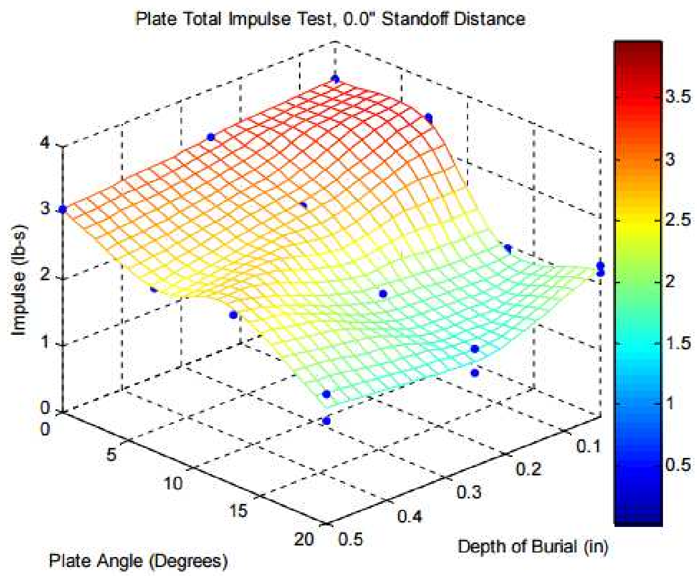


Figure 2.8: Effect of plate angle and depth of burial on total impulse by Genson (Genson, 2006)

Most of the present designs rely on a combination of the above to achieve the desired result and use materials made from high strength fibres like Kevlar® and Dyneema® to keep out fragments and use light weight honeycombed designed metal structures to act as attenuators with V shaped soles to deflect the blast. Inflatable soles and platform boots are designed to increase the surface area thereby distributing the weight of the person, resulting in lower force acting on the ground. These boots are designed for use when speed is the priority, since it allows for mined areas to be traversed rapidly from where an injured person must be recovered.

One major problem with designing mine boots is to find the balance between adequate protection without sacrificing much in the way of comfort. This is one of the major reasons why few of the effective designs are put into widespread use. The expectations of anti – personnel mine boots are relatively unknown, beyond obviously minimizing the amount of damage to the foot and lower limb to a salvageable extent. Precisely how the boot is supposed to accomplish this is unknown. Are the boots supposed to maintain complete integrity while allowing a small portion to deform or are they allowed to be completely deformed so as long as the foot is damaged only to a salvageable extent. Here salvageable extent might mean that if the boot is not completely able to protect the leg from the blast, it should be able to minimize the loads as much as possible while reducing the level of contamination. This might result in a better surgical outcome with a better rehabilitation rate.

2.4.1 Cellular materials

Previous studies have highlighted the effect that foams and other cellular materials can have on the energy and impulse transferred to the foot (Fujinaka et al, 1966; Mah et al, 2007). Since all boots contain either foam or rubber soles, it is necessary to get a better understanding into the mechanical behaviour of cellular materials.

Cellular materials are playing an increasingly important role in the protection, whether it is the insulation of delicate materials and equipment from heat or impact; or the protection of the human body from exposure to external traumas in the shape of high and low speed impacts from knocks and falls as well as in this case blast loading from explosions. Cellular materials such as foams are cost effective, lightweight and can be fabricated in a variety of shapes and sizes with predictable behavioural and material properties based predominantly on those of solid materials making them ideal for use in protection.

The structure of foams (cellular solids) is defined by the individual cell size, orientation and shape of the internal cells and the pre – formed solid material. Over the years many people have examined different aspects of cellular solids, but always referring back to the fundamental research of Hooke (Hooke, 1664) and Kelvin (Thomson, 1887) who between them analysed their shapes, their manufacture, functionality and how the cells were fitted together, along with their topology (where topology is the connectivity of the cell walls and of the pore space).

They noticed that cellular structures vary immensely, from regular structure of bee's honeycomb to that of cork, natural sponges, plant or animal structures, and that understanding their behaviour could be of great importance. Gibson and Ashby (1999) revived interest in previous research with their book Cellular Solids to characterise the shape, size and topology of the cells and pores and the geometric classes into which they fall. Their second edition explained that regular cellular structures may be either honeycombs or natural foams, with closed cell foams like cork or balsa, or open cell ones like sponge or cancellous bone.

Low density cellular solids appearing in nature stimulated interest in aspects of their structures, mechanical, thermal and other properties by mathematician, physicists, engineers and even food technologists. The aim was to determine how artificial cellular solids with appropriate properties could be manufactured and utilised. The result was to categorise the cellular structures into three basic types, namely open – cell, closed – cell and honeycombs.

Cellular materials can be fabricated from various solid materials in order to achieve specific behavioural characteristics that are suitable for an individual task or application. Metal foams are characterised as either hard and brittle or soft and ductile. In either case, metal foams show elastic perfectly plastic material behaviour where beyond a certain yield strength the material is permanently deformed. Rubber foams are primarily used for shock absorption, displaying large recoverable elastic deformation within their cell walls from the external loading (Kosten et al, 1938). Polymeric foams also experience large elastic deformation and can be either recoverable or irrecoverable in their ability to absorb energy, depending on the yield strength and the arrangement of polymer matrix. Ceramic foams that can be characterised as hard and brittle yet consist of highly densified cell walls and struts with low thermal conductivity, produce foams that display rigid non – deformable cellular properties (Sepulveda et al, 1999).

Rubber foams, can be found as thermal insulators, floatation devices, acoustic insulators and closed cell ‘one – use’ shock absorbing motorcycle clothing, but are primarily used as dampers or cushions to insulate against vibrations. In such applications they experience large elastic deformations when impacted which compresses the air inside the cells. Kosten and Zwikker (1938) represent this as a spring and dashpot arrangement where when a load is applied to the piston, it moves downward compressing the device for damping shock or vibrations is forced to return when the load is removed.

The behaviour of foams can be categorised based on their stress – strain curve when a force is applied to them. Stress is the force that is acting on the unit area of the foam and strain is the deformation the foam undergoes due to stress which is the ratio of the new length to the original length of the foam. The stress strain curve consists of three distinct stages – the elastic phase, the plateau phase and the densification phase. When a load is applied to a foam it undergoes compression, which is the elastic phase which is linear at low stresses where the slope is equal to the Young’s modulus (E). Further increases in load causes the cells in the foam to begin to collapse by elastic buckling and pushes the foam into the plateau phase where the stresses vary very little. When the opposite walls in the cells meet and touch due to further increase in loads, the foam undergoes densification since the foam cannot compress further. This is characterised by the sharp rise in stress. The elastic, plateau and densification phase is illustrated in the stress strain diagram for a polymeric foam under compression (figure 2.9) The magnitude of the stress – strain curve can be changed by altering the density. If the density is too low, the foam compresses quickly resulting in premature densification leading to a higher force obtained before all the energy has been dissipated. On the other hand, if the density is too high, the peak load measured will be higher before the plateau phase can be reached. This means that it is possible to increase the Young’s modulus, raise the plateau of stress and reduce the strain at which densification begins by increasing the density of the foam (Gibson and Ashby, 1999).

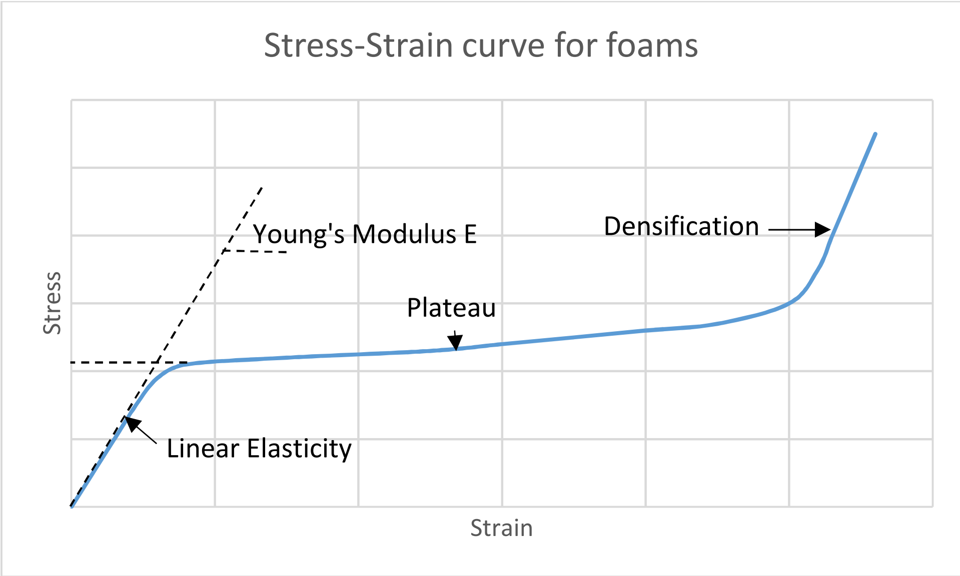


Figure 2.9: Stress – strain curve of polymeric foam under compression

2.4.1.1 Previous work on foams

Foams used in vehicles need to have optimum energy – absorbing properties to keep the force of the impact below a certain limit such that the deceleration of the occupants can be controlled safely. Polymeric foams can absorb a considerable amount of specific energy that is dissipated through cell bending and are suited for these applications. The stress is generally limited by the long and flat plateau of the stress – strain curve (figure 2.9). This enables the foam to give a maximum force lower than a solid specimen of the same material for the same amount of dissipated energy.

Zhang et al. (1998) performed static and dynamic loading on low – density polyurethane (PU), polypropylene (PP) and polystyrene (PS) foams. The paper showed that temperature has major effects on the constitutive behaviour of polymeric foam material, the polymeric foams become softer as temperature rises. The paper concluded that polymeric foam constitutive behaviour is extremely strain rate and temperature dependent. In addition, transitions of deformation and failure mode are observed as the loading conditions change. Foams behaving ductile under compression may fail as being brittle materials under shear and tension.

Avalle et al. (2001) looked into the mechanical properties of three polymeric foams namely (i) expanded polypropylene (EPP), (ii) rigid polyurethane foam (PUR) and (iii) a blend of polyamide reinforced with modified polyphenylene and polystyrene (NORYL

GTX). The energy absorbing characteristics were examined both through the energy – absorption diagram and through the efficiency diagram method. An energy – absorption diagram is obtained by plotting the absorbed energy as a function of stress, where the absorbed energy is the area under the stress strain curve. Using the energy – absorption diagram it is possible to isolate the foam for a particular application based on its performance. This is because a lighter foam with a lower density is able to absorb a prescribed amount of energy with large deformation because the plateau of the stress strain curve is lower and undergoes densification much faster. On the other hand, a heavier foam with a higher denser foam is able to absorb the same amount of energy but with higher stresses and lower deformation. The energy – absorption diagram can be used to isolate the foam with the intermediate density that is able to achieve the same amount of energy absorption but with lower stresses than the denser foam while undergoing deformation. An energy efficiency diagram is obtained by plotting efficiency against stress where efficiency is defined as the ratio of the absorbed energy divided by the stress.

For the testing 5 nominal densities of EPP, 2 nominal densities of PUR and 2 of NORYL GTX were considered. The foam specimens were tested under quasi – static and dynamic compression loading to determine the energy absorption characteristics and the impact behaviour.

It was found that (Avalle et al, 2001) at static loading, the efficiency of EPP foams is less than 40% and it decreases with an increase in foam density. In addition, the stress at maximum efficiency increases non – linearly as the foam density decreases. In the case of dynamic loading it was found that the effect of speed reduction was quite limited before densification is reached. However, it was noted that the energy absorbed at maximum efficiency was much higher when the foam was dynamically compressed although the stress is higher too. For PUR foams it was found that the maximum efficiency was about 50% with small differences between the two density values when compressed statically. The efficiency increases by a small margin when compressed dynamically although the energy absorbed is not significantly increased by the impact velocity. For NORYL GTX it was found that they had good efficiency of about 45% and can dissipate large amount of energy per unit volume.

All of this combined with the fact that foams are used in boots suggests that it is possible to reduce the energy transferred to the leg by changing the density of the foam. However, care has to be taken since this requires using a foam of higher density which means that the stress would also increase, thereby increasing the loads transmitted. This combined with the previous work on standoff distances (Fujinaka et al, 1966; Mah et al, 2007) means that it might be possible to affect the performance of a boot by changing the thickness of the sole and its density and requires further investigation.

2.5 Injury mechanism

The patterns of injury caused by blast are divided into primary, secondary and tertiary injuries. In addition, the term quaternary injuries are used to describe miscellaneous injuries. However, people suffering from blast injuries are not restricted to a particular type but usually involve a combination of them to one degree or another. These injures are called multidimensional injuries (Kluger et al, 2006).

When direct tissue damage is caused by the forces that are transmitted by the blast wave, the resulting effects are called Primary injuries. This includes three types of injuries: spallation, implosion and shearing. Since blast waves are more serious in closed spaces than open spaces, these forces have a concentrated effect in the regions of air – tissue interface resulting in a raised incidence of injury. When the shockwave passes through a medium, high stress points develop that are normalised by breaking down of the medium at the outer surface. This is known as spallation (Stuhmiller et al, 1991). Implosion occurs when the positive pressure phase passes causing rapid compression of the gaseous volume within tissues due to the blast overpressure. Once the shockwave passes the pressure drops leading to the re – expansion of the gas at high velocities releasing a large amount of kinetic energy leading to vascular and pulmonary injuries by causing damage to the blood vessels and alveoli in the lungs (Ho, 2002). Shearing occurs due to the difference in the densities of the different organs. As a result, when the blast overpressure travels through them, it results in the different organs moving at different velocities due to which shearing forces are developed at the attachment of the organs and can be damaged by these shearing forces. In addition, spallation at the boundaries of the different tissues would result in additional shearing forces due to the breakdown of the tissues (Wolf et al, 2009).

Since the blast overpressure produces blast winds, the debris in the vicinity of the blast is physically displaced and may lead to injuries (DePalma et al, 2005). This leads to penetrating and blunt trauma injuries or a combination of them. This is further exacerbated by the fragments and debris from the mine casing, boots and soil. All of this combined produces what is known as secondary blast injuries.

When the blast winds physically displace a person from the vicinity of the blast and leads to blunt trauma injuries due to collision with the surrounding, it is known as tertiary blast injuries. This would also include the acceleration of the leg as a result of the blast which exceeds the tolerance of the leg and leads to fractures and is one of the mechanism of damage to the upper leg. Tertiary blast injuries may even include injuries sustained by the collapse of building or other structures in the vicinity of the blast (Garner et al, 2007).

Quaternary blast injuries are those injuries which are caused by the blast but do not fall under primary, secondary or tertiary blast injuries. They include but are not limited to burns, toxic substance exposure, contamination, asphyxia and psychological trauma (Wolf et al, 2009).

While the physics of the blast have been well documented, the mechanisms of lower extremity injures are less understood. Mine blast that occurs near a person primarily cause thermal, blast (Wolf et al, 2009) and fragmentation injuries. Each contribute to the wound, but due to the speed at which the damage occurs it is difficult to determine which mechanism dominates. When the mine explodes the blast wave transmits through the mine case disintegrating it, then passes through the soil, the boot and finally enters into the foot. The force that accelerates the foot and lower leg upwards are usually greater than the lower leg can withstand, causing the bones to fail and fracture. In some cases, the force might be great enough that the bones might shatter completely (Hull, 1990). The force cause flexion and extension in the knee joint causing the lower limb to rise and flex prior to extending again. The force and the velocity transmitted to the leg exceed the tolerance limits of the tendons and the ligaments in the leg causing tears (Hull, 1995). The blast wave passes through the leg; the difference in the impedance of the different tissues causes a part of the blast wave to be reflected at the interfaces causing damage at the cellular level (Hull, 1996). From a macroscopic point of view, the very high pressure near the explosion source overwhelms the strength of the human tissue, causing disintegration. The waves are propagated through the bones, blood vessels and soft tissue and can be detected as far as the upper thigh. In addition, the waves might cause demyelination of the nerves up to 30cm above the area of injury (Nechaev et al, 1984). The stress wave and the blast destroy the lower attachment of the long muscle of the lower leg leading to the stripping of the soft tissue away from the long bones. In addition, fanning of the soft tissues takes place during the explosion allowing the ingress of the fragments from the destroyed foot, environmental debris and hot gas between the soft tissues in the direction radiating from the mine explosion. Micro – organisms from the soil are carried by the gases to the fascial planes where they contaminate the tissue. Post blast, the damaged tissue provides the best breeding ground for the bacteria due to the abundance of fat, blood and tissues deprived of vascular flow, leading to infection and sepsis. The detonation causes displacement and the products of the detonation may further injure the soft tissues (figure 2.10) (Trimble et al, 2001).

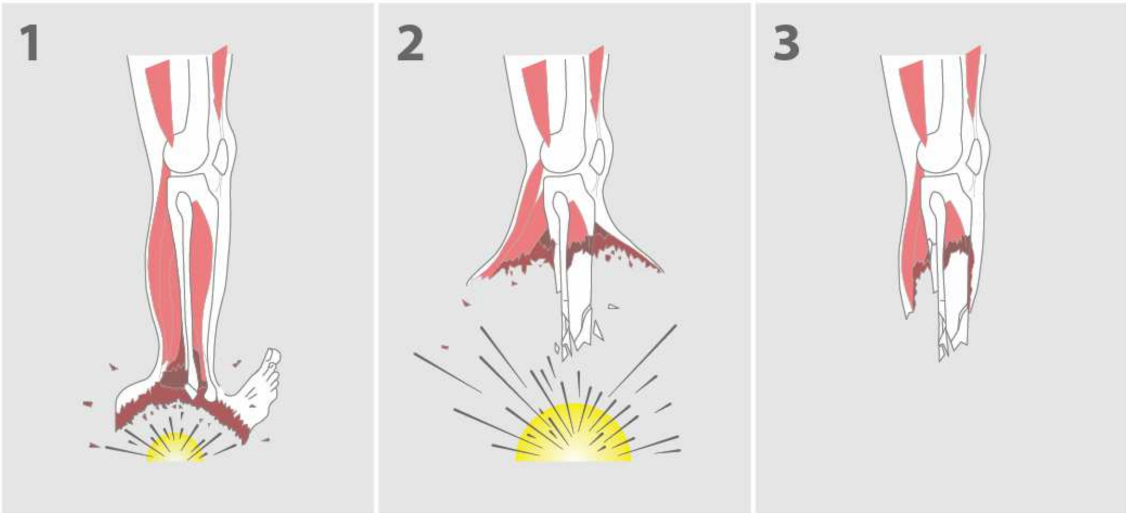


Figure 2.10: Traumatic below knee amputation

Hence, by reducing the energy transferred into the leg, the amount of surgery required can be minimized, which may result in better protection of the soft tissue and bone, thus allowing for a quicker rehabilitation. In addition, it is essential that there is not a path for environmental debris such as soil and fragments to enter the leg which can only be achieved by ensuring that the boots are not penetrated (Rountree et al, 2000). Bergeron showed that for a small blast mine, the heel undergoes severe damage even when additional protection is worn in the form an over boot (Bergeron et al, 2006). Hence, a good mine boot would be one that would be able to provide adequate performance even against a moderately sized mine such that the heel undergoes a minimum amount of damage. This would ensure that post rehabilitation, the victim would be able to gain back most of their mobility. However, research has shown that this is not possible yet, and even the best mine boots such as the spider boots only offer adequate protection against a relatively small mine and even then it has resulted in fracturing of the heel with the need for debridement as a result of contamination from environmental debris (Van der Horst et al, 2008). If the patient suffers from consistent pain due to nerve damage, then saving the leg is not the best surgical outcome and there would be an argument to be made about amputation and being fitted with a prosthetic limb (Hansen, 2001). This is where the literature suggests taking into consideration the increase in the energy expenditure relative to the level of amputation. If amputation is required, rehabilitation is much more successful if the knee joint is preserved. Due to the difficulties in production and fitting prosthetics for through – knee amputation, they are seldom undertaken. In addition, the increase in the energy expenditure is 25% over baseline for a young amputee with a trans – tibial amputation, 40% for a bilateral trans – tibial amputations (Traugh et al, 1975), 65% for a trans – femoral amputation and 150% for a bilateral trans – femoral amputation (Gonzalez et al, 1974). Hence, with minimal energy increase, it is possible to get near normal function and mobility in certain daily activities in young people with trans – tibial amputation.

From the above information (Rountree et al, 2000; Trimble et al, 2001) it can be seen that despite the blast destroying the lower limbs; it is not the major threat. Rather the most important factor to be minimized is the degree of contamination. The literature (Fujinaka et al, 1966; Harris et al, 2000; Van der Horst et al, 2008; Nicol, 2011) suggests that despite the progress made in novel anti – personnel boot design only a few of them are capable of providing a certain degree of protection against a mine, and even then the protection is limited depending on the size of the mine resulting in damage to the leg; with none offering complete protection. Hence, the question is whether the level of injury can be reduced such that it requires a minimal amount of surgical intervention from which a person can make a good functional recovery. Hence, it might be beneficial to break down the protection offered by the boot into two systems, one which reduces the loads transferred to the leg and another which minimizes the level of contamination. It might be possible to strike a balance between the two that would allow a surgical outcome that minimizes the level of amputation.

2.6 Previous work on blast mines

Lans (1999) evaluated protective footwear when exposed to contact explosion. An experimental setup was designed in order to mimic human motion. In order to simulate a human leg a steel pipe was used which rotated at the knee and hip. This gave the leg assembly a total weight of 16kg. The leg was connected with a steel plate of thickness 5mm in order to simulate the foot. Human tissues were mimicked by encasing the entire assembly in 20% gelatine which was poured into the boot after the foot had been placed in.

To mimic a real world situation and to get an idea of the worst case scenario possible the mine was placed under the ball of the feet buried a few centimetres under the sand. The mine used had a charge weight of 57g which was representative of most of the common smaller mines found at the time (King, 1998). To get the data regarding the acceleration the foot underwent at the time of the blast high speed cameras were used which recorded everything through a mirror.

For the purpose of testing two types of boots were used. The first was the BFR™[1] Combat Boot, Singapore, which was re – enforced with aramid layers. The boot was supposed to be blast and fragmentation resistant. The second was the Wellco[2] Combat boot and Over boot. The boot had a V – shaped rubber outsole and a multi – layer Kevlar insole with a wedge of metallic honeycomb between them. The boot was supposed to be blast protective. In addition, standard Dutch army combat boots were used for reference.

The paper (Lans, 1999) demonstrated that despite the claims by the companies of both the blast protective boots, they do not offer adequate protection when exposed to a contact explosion. In all of the cases the front of the foot was completely destroyed and blown away.

Harris et al. (2000) dealt with the medical diagnosis of landmine injury and the assessment of injury severity – the Mine Trauma Score. The tests were done by using cadaveric limbs and a combination of various mine boots and over boots against a selection of mines like the PMN, PMA – 2 and the M – 14. The purpose of this was to assign a value to the degree of protection offered by the boots based on the severity of the damage to the lower limb so that the results could be compared to other literature thus creating a universal method to assign a value of landmine injury.

The report (Harris et al, 2000) concluded that the countermine boots available at the time did not prevent severe injury even against a small charge. Of the tests conducted on the cadaveric limbs other than a few cases where a combination of Wellco boot and over boot was used all of them resulted in damage which would have led to amputation. Even though the Wellco boot and over boot combination prevented amputation it still resulted in severe hind foot, ankle injuries and tibia fractures.

The Lower Extremity Assessment Program (LEAP) (Harris et al, 2000) was sponsored by the United States Humanitarian Demining Program as a way to assess the effect of landmine blast on human foot as a function of protective footwear. The tests were used to

[1] BFR Boots, Hong Kong.
[2] Original Footwear, Eersel, Netherlands.

provide detailed information about injuries to human tissues as a consequence of land mine blasts on cadaveric legs. One of the major problems in this was that cadaver legs were not representative of the personnel who usually step on land. This is because the cadavers used for the LEAP trials ranged from 37 to 96 years of age and weighed from 44 to 93kg. In addition, specimens are not capable of showing a response to external stimulus unlike live specimens which tense and flex when forces are exerted on them. This would result in different results between the two.

For this purpose, surrogate legs like the Canadian lower legs and the Australian frangible surrogate leg were developed. The main purpose of Canadian Centre of Mine Action Technologies (CCMAT) tests by Bergeron et al. (2006) was to test the feasibility of frangible surrogate legs as a replacement to cadaveric legs and to develop a mine blast injury criterion that might be used to study the blast protection of protective footwear. Frangible surrogate legs or Canadian lower legs are physically accurate models of the human leg that were developed in response to survivability against landmines. They are constructed from materials simulating bone, cartilage, connective tissue and soft tissue and are engineered to produce reproducible responses to loading while having substantial anatomical accuracy (Holland, 2011). For this purpose, the CCMAT tests were performed in the same way as LEAP tests were performed. The purpose was to develop a database of injuries to frangible surrogate legs from land mines to be compared to the results obtained from LEAP.

In all of the cases the frangible surrogate legs were fitted with two types of boots – the Canadian army MK III or the Wellco blast boot. The mines that were used were the PMA – 2 which contained 100g of TNT explosive and PMA – 3 containing 33g of Tetryl. In addition, VS – 50 mines were used containing 43g of RDX. The mines were buried a few millimetres below the surface with the heel of the boot right above the centre of the mine to simulate the worst case scenario.

The paper demonstrated that the frangible surrogate legs performance was comparable to the results from LEAP using cadaveric legs when subjected to the same explosive stimulus. In addition, it was also capable of producing different results when the stimulus and the level of protection were changed. However, it was not possible to correlate the level of injury sustained by the frangible surrogate legs to the cadavers of LEAP since the mines used in LEAP couldn't be obtained, and hence more powerful PMA – 3 mines were used.

For the purpose of recording the level of injury flash X – rays were used. The paper hypothesised that there is a hemispherical zone of high pressure gas that imparts localised damage to those parts of the foot wear in the immediate vicinity of the mine. The vertical push from the mine is particularly focused in a small zone directly above the mine as evidenced by the deformation of the blast boot deflector in the sole of the Wellco blast boot. In addition, it was seen that when a protective over boot is used in conjunction with the blast boot, there was significant damage to the deflector in the over boot which was transferred to the deflector in the protective boot. Hence, the inclusion of solid objects in the boot must be done with care, since the blast is capable of imparting momentum to any such object which can become a projectile capable of penetrating the foot.

The test conducted on the boots in isolation correlated with the data from previous studies and concluded that even the smallest of mines destroyed the footwear and resulted in amputation above the ankle. Whilst inclusion of additional protective footwear reduces some of the force of the explosion by distancing the foot from the zone of very high pressure close to the mine, it still resulted is permanent deformation of the deflectors and the arch of the boot. As the weight of the charge increased the arch deformed further and tears appeared in the inner boot and in some cases the frangible surrogate legs foot burst open.

When tested with Spider boots (figure 2.3), the standoff distance combined with the detonation of the mine away from the heel resulted in preservation of the structural integrity of the boot for all tests. However, X – rays clearly showed that there was a potential for injury due to the deformation of the deflector due to the impulse applied by the gas pressure and the soil ejecta.

The first phase of the report concluded that although the data from the frangible surrogate legs correlates with that obtained during LEAP, it would be beneficial to decrease the strength of the calcaneus and talus bones of the frangible surrogate legs, and use only the lower segment of the frangible surrogate legs since the damage was concentrated on the distal leg. In addition, the paper concluded from the medical assessment of the frangible surrogate legs that the Mine Trauma Score (MTS) system was the only viable option as other system like AIS[1] and NISSA[2] were too coarse, relying on systematic responses only existing with

[1] Abbreviated Injury Scale.
[2] Nerve injury, ischemia, soft tissue injury, skeletal injury and age of the patient score.

live patients, while ICRC[1] although more applicable that the other two lumped all injuries as below knee or above knee amputations. The MTS system was developed as part of the LEAP trials to compare the severity of mine injuries with respect to the protective effect of the footwear based on the evaluation by a surgeon. While the vast majority of landmine injuries will result in trans – tibial or trans – femoral amputation (Coupland, 1991), the MTS includes values for lesser injuries making them applicable to smaller mines (table 2.1 and table 2.2).

Table 2.1: Mine Trauma Score system (Harris et al, 2000)

Injury assessment	MTS	Injury
No major injury	0	
Salvageable limb	1	Closed
	1A	Open contained
	1B	Open contaminated
Trans – tibial amputation	2	Closed
	2A	Open contained
	2B	Open contaminated
Trans – tibial/trans – femoral	3	
Trans – femoral	4	

[1] International Committee of the Red Cross score.

Table 2.2: Mine Trauma Score system injury description (Harris et al, 2000)

Injury	Description
Closed Injury	Injury of the lower leg that does not violate the skin, but may include fractures affecting the outcome but eliminating the chance of infection
Open contained injury	Injury of the lower leg where the skin is breached but no signs of contamination
Open contaminated	Injury to the lower leg where the skin is breached and the soft tissue is visibly contaminated by environmental debris such as soil, foot wear debris and mine fragments
Salvageable limb	Injury to the lower leg where injury doesn't mean amputation is inevitable
Trans – tibial/trans – femoral amputation	When the injury to the lower leg extends to the proximal third of the tibia and there is not salvageable soft tissue

In addition, it was noted that the MTS score for the PMA – 3 mines were lower than the M – 14 mines used during the LEAP trials. This was contradictory as the PMA – 3 mines had a greater explosive charge than the M – 14. This result was partly explained by behaviour of the gelatine that is used to replicate soft tissues. While in human tissues, the gas travels along self – dissecting planes along the facia that divide the compartments of the leg, the gelatine behaves differently by attenuating the vertical propagation of the detonation products (Bergeron et al, 2006).

In 2007, Phase II of the report (Bergeron et al, 2007) incorporated all the recommendations of Phase I and tested the frangible surrogate legs with M – 14 mines. Similar results were obtained as that of Phase I. When the frangible surrogate legs were used with the blast boot it resulted in the significant destruction of the frangible surrogate legs due to overpressure. When the frangible surrogate legs were used with the blast boot together with the over boot, the sole of the over boot was destroyed and the deflector in the over boot was vertically accelerated such that it impinged onto the deflector in the sole of the blast boot and accelerating it, as was observed in Phase I of the trials referenced earlier (Bergeron et al, 2006). In this case the over boot was not breached indicating the cause of the damage was blunt trauma due to the blast deflector. However, when the test was repeated with against a PMA – 2 mine having a larger charge weight, due to the larger over pressures generated, similar behaviour was seen in the blast deflectors but the distal leg burst from the inside out.

Examination of the frangible surrogate legs revealed that since the calcaneus and talus bones were decreased in strength to more accurately reflect that of the human leg, it resulted in a MTS that meant that only one out of four legs would be salvageable (Bergeron et al, 2007).

Van der Horst et al. (2008) looked at the protection level and injury response of several mine boots using different surrogate legs. The paper looked at the performance of eight different mine boots with respect to several parameters using two different types of surrogate legs – Frangible surrogate leg and the Canadian lower leg. The tests were conducted according to guidelines set out in 'NATO Test methodologies for personal protective equipment against anti – personnel mine blast' (NATO TR – HFM – 089, 2004).

In order to simulate the vertical movement of the leg a long piston was used with wheels for support to minimize friction. This represented the upper leg of a person standing vertical. Eight boot types were selected for testing, with the spider boot (figure 2.3) as a typical example of a platform boot whereas the others are more or less conventional boots, including the Combat Boot of the Dutch army which was used as a reference. Charge weight of 25g, 50g and 75g were used which were buried 20mm under the surface and were placed under the heel in order to simulate the worst case scenario. The study (Van der Horst et al, 2008) found that with even at 25g of explosive charge, none of the conventional boots provided adequate protection and resulted in a trauma score relating to below – knee amputation. The Spider boot was found to provide adequate protection up to 75g without the need for below – knee amputation, but still required fixation of the ankle and debridement of the wound. Although the Spider boot was found to have the lowest injury score, it also had the highest score for discomfort. Charge weight of 50g and above was found to cause extensive damage to both the mine boots and the limb bones to such an extent that only two tests at 75g were performed. The charges were placed directly below the heel of the boot, in order to simulate a worse – case scenario where the greatest weight is placed directly above the explosive mine, and buried at a depth of 20mm in sand, as it is most often the case that anti – personnel mines are buried rather than flush with the environment medium.

The paper (Van der Horst et al, 2008) concluded that the data obtained from the force transducer and displacement sensor could be used as a preliminary predictor of the MTS (table 2.1 and table 2.2) score with a higher force value correlating to a higher MTS score. The spider boot showed a relative low force and also the injury score was the lowest of all mine boot concepts tested. The paper also concluded that the boot damage cannot be used as a predictor of the foot/leg injuries. Several boots displayed little surface damage but were not able to mitigate the blast that was transferred to the leg, resulting in high loads measured and many fractures of the foot and ankle structure. In addition, the paper also noted that displacement was larger at smaller charge weights than larger ones for the same boots and in some boots the forces measured were greater at smaller charge weights than larger ones. A possible explanation given was that the response mode changes above a certain level resulting in different forces and displacement.

Bass et al. (2004) used force data from a Hybrid 3 surrogate limb to assess the performance of different boots against land mines by developing an injury risk function. The study developed a three level grading procedure for boot damage –BD1, BD2 and BD3 (table 2.3). These corresponded to minor external damage to severe damage with major boot contamination breach. The paper demonstrated that boot damage can be used as only a preliminary indicator of the blast performance of the boot. Secondary assessment is required in the form of force sensor data since there were several cases in which several injuries were obtained in spite of the boot damage level being 1. An injury risk function was calculated from the data which showed that the risk of injury exceeds 50% above 8600N axial load (Bass et al, 2004).

Table 2.3: Boot damage criteria (Bass et al, 2004)

Boot damage level	Description of damage level
BD1	Minor damage to boot (i.e. portion of sole blown off, insole destruction)
BD2	Structural damage to boot (i.e. minor blast penetration into foot compartment of boot)
BD3	Breach (i.e. massive blast penetration into foot compartment of boot)

Hlady (2004) looked at the effects of different parameters that influenced landmine blasts in Concrete Fine Aggregate Sand and Prairie soil. Hlady showed that for prairie soil for a given overburden and standoff as the moisture increases the energy transfer to the target increases. An example was for 50mm overburden and 6% moisture the energy transfer was 36J which increased to 186J at 20% moisture – an increase of 500%. However, this cannot be explained by the equation by Tremblay (1998) which gives a total impulse calculation of 99N.s. This is because the Tremblay equation is empirical and is only validated for relatively dry soils, hence it cannot account for the differences in energy observed between dry and wet soil.

The paper also showed that there is an optimum burial depth for energy transfer, when there is no burial depth the energy transfer is reduced and conversely if there is too large of a burial depth the soil tends to absorb most of the explosive energy. It was found that the optimum burial depth for 25g of C4 was 50mm beyond which it decreases. Another aspect that was looked at was cohesion, sand which is less cohesive tends to produce a fairly uniform eject which is not the case with prairie soil where cohesion is much higher. A similar detonation resulted in large chunks of soil being ejected. Finally, it was found that increasing the standoff distance by as much as 50% reduced the energy transfer by 60% (Hlady, 2004). This was further confirmed by Cheeseman et al. (2006) when comparing numerical models to actual blast tests. The paper concluded that burial depths can affect the time period of the blast wave and the magnitude of the total impulse, with higher burial depths increasing the time duration but also increasing the magnitude of the total impulse. This makes sense since from the Tremblay (1998) equation it can be seen that the total impulse value is directly proportional to the burial depth, hence if the depth of burial is changed from 50mm to 100mm the total impulse value increases from 99 to 161N.s. However, the issue is that the Tremblay equation is validated only for a limited range of burial depth and according to the equation it would keep on increasing as depth increases which is not the case as shown by Hlady (2004), where there is an optimum burial depth beyond which energy transfer drops.

Nicol (2011) looked at the performance of a particular anti – personnel mine boot both non – destructively to determine how the anti – personnel mine boots influence the loads transferred and destructively using 35g and 50g of PE4 charge which were buried at different depths. These results were compared to tests using commercially available combat boots under the same condition. Since the anti – personnel mine boots were rated for a 35g charge, testing was conducted at 50g to determine the performance that would be afforded if the boots were over matched. The research provided results that matched those that were previously observed in the literature. At impact velocities of 5.5m/s which are lower that the velocities observed during a blast test, using a drop tower, all the boots other than the anti – personnel mine boot resulted in loads exceeding the fracture threshold of the lower limb (8.6kN). This lines up with the literature where increasing the standoff distance decreases the loads transferred, which was true for the anti – personnel mine boot since it had the greatest standoff distance. However, since the standoff medium is foam in the case of the anti – personnel mine boot, the performance would be inferior compared to spider boots that has air as the standoff medium, when the standoff distance for the two is the same (Mah et al, 2007).

With respect to the blast tests at both 35g and 50g, at all burial depths the loads measured exceeded the fracture threshold by several times for all the boots and other than a single trial where the anti – personnel mine boot prevented contamination from environmental debris and survived the blast, it failed to do so in the other cases. Since this test was not repeated again it is difficult to conclude if this was due to the boot having the optimum condition of burial depth and charge weights or if it was just an anomaly in the experiment, since in all the other cases it failed to protect against the blast. Additionally, the boot damage post blast was categorised using the boot damage criteria used by Bass et al. (2004) and it showed that even though in all the cases the loads measured were high it didn't mean that the level of boot damage was the same in all the cases, with some of the commercially available combat boots offering adequate contamination protection against the blast in terms of contamination prevention resulting in a lower boot damage criteria value. The data showed that none of the boots provide adequate protection against either the 35g or 50g charge in terms of reducing the loads measured. And while the anti – personnel mine boots offer some degree of protection it is not sufficient enough to prevent serious injuries. The work concluded that it might be more beneficial to look at the failure mechanisms involved in the boots. From the testing it was observed that the boots that had better overall construction such as proper seals around the heels in the boot, although they did not offer adequate minimization in the peak forces experienced, offered the best protection against invading contaminants and remained completely sealed post explosion. The literature (Rountree et al, 2000; Trimble et al, 2001) identifies that other than the compressive fractures as a consequence of blast, the second most dangerous factor to consider is the ingress of contaminants. By tackling this problem, it might be possible to achieve an adequate degree of protection from anti – personnel mine boots.

All of this highlights the issues with current anti – personnel mine boots and blast testing; anti – personnel mine boots have fixed specifications under which they perform optimally. However, in a real world scenario this would not provide the best conditions for the anti – personnel mine boots where the charge weights could be well out of the specifications in addition to how differences in other variables like soil types and moisture content would drastically alter the outcome of the blast resulting in sub – par performance of the boot. This is where it might be more beneficial to assess the performance of commercially available boots, which can be worn continuously throughout the operation and provides adequate protection while striking a balance between ergonomics allowing for adequate mobility while meeting the requirements for the best possible surgical outcome.

2.7 Problems with current test methods

NATO standards (NATO TR – HFM – 089, 2004) HFM – 089 specifies the recommended guidelines for mine tests, however since most of the studies pre – date the standard, it makes comparison of the results quite difficult. In addition, there are quite a number of variables involved in mine tests which make it necessary to identify all of these variable and deal with them.

Setting up the test environment for simulating a land mine blast is a complicated issue. Obtaining appropriate quantities of a particular mine is quite difficult, added to which same mines have widely different behaviour depending on the soil and environmental conditions. To develop an objective test procedure, the test conditions should be realistic yet repeatable, which puts constraints on the costs and the number of tests performed to effectively characterize the protective equipment. Hence, the mine should be simulated by a well characterized plastic explosive, implanted at known depths within well characterized soil. Charges should be selected that characterize the broad spectrum of anti – personnel mines that would be encountered. HFM – 089 states that a good category for measurement would be the pressure time history by using a free field pressure sensor; these would give an indication of the robustness of response, repeatability and differentiation between the different charges. In addition, a force transducer could be used to obtain measurements of loads and impulse transmitted.

Collecting accurate data regarding the effects that blast has on human tissue is quite difficult. This is because the testing is primarily done using surrogates and the data has to be related back in some way that reflects the damage on human tissue. Human tissue is the most accurate since the data can be directly related to damage, however there are ethical and health and safety concerns when biological samples are used. Moreover, there is a large variability in the mechanical properties of the bones such as density and load threshold, since they are amputated legs generally coming from the elderly population (Chaloner et al, 2002). Limbs that are used for this type of testing are usually obtained from cadavers that belong to an older age group and are not representative of the personnel that might step on a land mine.

A variety of surrogate types have been used in blast testing of protective equipment, from metal rods and a metal plate to simulate a leg, to frangible surrogate legs that incorporate ballistic gelatine as a human soft tissue simulant (Harris et al, 2000; Chaloner et al, 2002; Bergeron et al, 2006). While simpler synthetic models, such as metal surrogates or wooden blocks can provide useful data with respect to loads and pressures produced during a blast allowing for the assessment of protective equipment; they cannot be correlated to actual damage to the leg. Frangible surrogates are completely synthetic and are designed to match the specifications of a human leg both in terms of structural accuracy and load limits. They are a good solution to conduct more accurate analysis once basic observations have been made using a simpler synthetic model such as metal surrogates. A series of recent tests (Bergeron et al, 2007) comparing results of tests done on the frangible surrogate leg with the human cadaver work from the LEAP (Berlin et al, 1977) programme in the United States has produced good correlation between the two. However, frangible surrogate legs are quite expensive, costing approximately £1500 per leg. Since they are destroyed in every blast test, it makes the experimental trial quite expensive and puts a limit on how many can be performed. An alternative solution would be to use Hybrid 3 legs. Hybrid 3 are full scale anthropomorphic test devices that are used to study the effects of crash on the human body. The legs of Hybrid 3 are more robust than frangible surrogate legs and can be used multiple times in addition to containing the necessary instrumentation. A major drawback with them however, is that they do not have a tissue simulant making it impossible to study contamination effects of blast. Moreover, they cost the same as the frangible surrogate legs, still making it an expensive process.

An alternative to human cadaveric legs is red deer tibia that similar structural integrity to the human bone (H.P. White Laboratories, 1998; Cronin et al, 2004)). They are easy to obtain and allow for the tighter control of quality since it is possible to select the age of the animal from which it comes.

Metal surrogates allow for basic instrumentation data to be collected which allows for early evaluation of protective footwear being tested and helps narrow down the selection of boots. Baseline data can be collected in the form of loads, impulse, acceleration and displacement of the boot, although the load data can be compromised by the reflection of the blast wave within the metal surrogate (Cronin et al, 2004).

Testing the effectiveness of blast protective footwear is a complicated problem. The work done to date has raised more questions than those were answered. At present there is not a consensus on which factors are important in determining the performance of a product in terms of protection. There is a lack of standardization between the different methodologies used that makes it difficult to compare them. A standardization of the methodology would enable one to conduct a thorough evaluation of the protection offered by different properties, and serve to eliminate extreme claims made by products without extensive testing.

2.8 Gelatine as a tissue simulant

Since it is important to study the contamination effects of blast on tissue, it is necessary to use a simulant that is able to be used for this. Gelatine has been used for a long time as a soft tissue simulant, hence it is necessary to get a thorough understanding of how it has been used and how it is applicable to this research.

2.8.1 Ballistic gelatine

Ballistic gelatine is widely used as a soft tissue simulant to evaluate penetrative, blunt impact and blast loading effects on soft tissue. It has been used as a tissue simulant to study the penetrating effects of ammunitions due to the similarity of its density and viscosity to human tissue. Ballistic gelatine allows for its properties to be carefully controlled to meet the performance of human tissue while overcoming the ethical and health and safety restrictions.

The basis (Sellier et al, 1994) of the use of gelatine as a soft tissue simulant is from early penetration studies where gelatine was able to reproduce penetration depth in soft tissue (Jussila, 2004) and demonstrate the mechanics of temporary and permanent cavities resulting from an impact (Fackler, 1987).

Human legs are structurally very complex; with complex bone structures and tissue attachments making it difficult to design a simulant that meets its specifications. Effectiveness of 20% gelatine as a tissue simulant was studied by comparing the performance of human cadaveric legs (Coudane et al, 1982) against human cadaveric distal femurs and tibia that was cast in 20% gelatine (Ragsdale et al, 1988).

While both 10% and 20% are good replacements to be used as soft tissue simulants, there is an argument to be made for 20% gelatine since it more closely matches the specific gravity of muscle tissue of 1.06 (Janzon et al, 1997) (table 2.4). The density of ballistic gelatine is similar to that of soft tissue (approximately 1060kg/m^3). Experiment done by Van Bree et al. (1996) measured the stress waves in 20% gelatine and found that they have a speed of 1540 – 1550m/s which were consistent with the accepted value of 1580m/s in muscle tissue (Fung, 2013). Hence, 20% Gelatine will be used for this work.

Table 2.4: Specific gravity of human tissues (DeMuth et al, 1966)

Tissue	Specific gravity
Fat	0.8
Liver	1.01 – 1.02
Skin	1.09
Muscle	1.02 – 1.04
Lung	0.4 – 0.5
Bone	1.11

2.8.2 Review of the work done on ballistic gelatine

Fackler et al. (1967) looked at the detrimental effects heating had during the preparation of ballistic gelatine. Based on the data provided by the Institute of America Fackler (Gelatine Manufacturers Institute of America Inc., 1982) stated that heating Gelatine above 40°C would have detrimental effects on its ballistic properties, which is in line with the recent work done by Cronin (Cronin et al, 2011), however this contradicts the data given by the manufacturer in the work done by Jussila (Jussila, 2004) which states that the gelling power does not significantly decrease after several hours at a temperature between 40 – 80°C.

According to Fackler et al. (1967) the most useful properties of Gelatine, which are the gel strength and viscosity, gradually weaken on prolonged heating in a solution above 40°C. In order to minimize the detrimental effect of heat on the ballistic properties of Gelatine, a test procedure was developed to be followed:

1. Start with 70°C water.
2. Always add Gelatine powder to the water and never water to Gelatine.
3. Wet all the particles by minor agitation taking care to minimize the amount of air trapped.
4. Let the mixture stand in a refrigerator for 2 hours to hydrate all the particles.
5. Heat the mixture in a hot water bath at 70°C and stir till all the Gelatine is in solution and is evenly distributed.

6. Pour the Gelatine into moulds and let it set in a refrigerator at 7 – 10^{o}C.
7. After removal from the moulds store them in a refrigerator at 4^{o}C in air tight plastic bags.
8. Make sure that the blocks are not used for at least 36 hours after they were cast into moulds.
9. Mould can be inhibited by the addition of 5ml of propionic acid.

Fackler et al. (1967) discovered that if boiling water was used to prepare gelatine this resulted in extremely large temporal cavities in spite of the cracks being very small. It is understood that the excess heat weakened the gelatine's strength such that it provided less resistance than usual to being displaced by the temporal cavity.

The paper identifies that heating above 40^{o}C for short periods of time will probably not have any detrimental effects on the properties but in order to minimize the degree of error, care should be taken to follow the above outlined procedure.

Developing on the work done by Fackler (1967), Cronin (Cronin et al, 2011) looked at the characterisation of 10% gelatine in order to quantify the properties of gelatine that are sensitive to temperature and ageing. The paper showed that the temperature had an effect on stress at failure and material stiffness. While the penetration resistance was consistent after 72 hours of aging, it resulted in increased failure stress and in all cases, the samples compressed uniformly between the metal plates for the duration of the test. In compressive testing by Cronin (2011) gelatine samples exhibited hyperplastic stress – strain response, where the material stiffness increased with increasing strain rate up to the point of failure. Evaluation of ageing on penetration depth's showed that beyond 72 hours' penetration was within the margin of error.

When a bullet is fired into a ballistic medium it is decelerated and for a period of hundreds of microseconds the medium is stretched perpendicularly to the trajectory which is called ''temporary cavity''. Schyma et al. (2012) evaluated the temporary cavity using different methods to determine the energy dissipated in ballistic gelatine. By measuring the total crack lengths (TCL) along a gunshot wound channel it is possible to calculate the energy transferred by a projectile to the surrounding tissue along its course. Visual quantitative TCL analysis of cut slices in ordnance gelatine blocks is unreliable due to the poor visibility of cracks and the likely introduction of secondary cracks resulting from slicing. Bollinger et al. (2010) showed that it is possible to calculate the energy transfer by taking CT measurements of the TCL. Crack length (Ragsdale et al, 1988) based methods – like the wound profile and the TCL – and destruction area (Schyma, 2010) based methods show a strong dependence of the gelatine destruction and the energy dissipated.

2.8.3 Preparing ballistic gelatine

The first to use gelatine as a ballistic simulant was Harvey (1948) in the 1940's. He used 20% concentration at 24^{o}C. Lewis et al. (1982) prepared gelatine using 90–95^{o}C water and adding 3ml of cinnamon oil as microbial growth inhibitor (MGI). The solution was cured for an hour before it was poured into mould and left undisturbed overnight. They were then stored at 5–8^{o}C tightly wrapped in plastic. The most referred recipe for gelatine is that of Fackler and Malinowski (Fackler et al, 1967). They recommended using 10% solution by pouring the gelatine powder into cold (7–10^{o}C) water, maxing and storing in a refrigerator for 2 hours. The solution is then heated in water bath to 40^{o}C and stirred until all gelatine has dissolved, into which 5ml of propionic acid was added for every litre of the gelatine solution. The solution is poured into moulds and set into a refrigerator (7–10^{o}C) for overnight. The blocks are then removed from moulds, wrapped tightly in plastic bags and stored in the refrigerator at 4^{o}C for at least 36h before use. As the method is rather awkward several modifications have appeared. Berlin et al. (1977) mixed 20% of gelatine straight into distilled water at 85–90^{o}C, used no MGI and let the solution stand in a refrigerator at 4^{o}C for a minimum of 72h. The gelatine was conditioned to 20^{o}C before use.

Firearms Tactical Institute (Firearms Tactical Institute, 2000) recommend dissolving 1000g of gelatine into 6L of hot tap water (49–60^{o}C) and mixing well, add 5ml of propionic acid and then three more litres of water (49–60^{o}C). The filled moulds are allowed to stand in room temperature for 4 hours before placing them in a refrigerator (4^{o}C) for at least 48h.

Jussila (2004) proposed a standard procedure to prepare ballistic gelatine. The research looked into the variables of preparing ballistic gelatine and their effects on penetration resistance. It was found that the effect of water temperature and acidity on the performance of gelatine is minor, which is balanced by the ability to prepare blocks that have consistent ballistic properties. Hence, as long the results are measured accurately, it should be possible to extrapolate them to reflect what happens in tissue, and the differences between the biomechanical properties of the two should not affect the result.

2.9 Summary of the literature review

The literature review of the topics related to the research question has highlighted points that this thesis will develop on.

The work done on foams (Avalle et al, 2001) has highlighted the effect that densities and the standoff distance foams can have on the energy transferred. Since, boot soles are composed of foam, the next logical step is to determine how the combination of changing the density and the foam thickness would affect the load and the total impulse measured. The foams used should have a spread of densities and thicknesses that would be used in different boots. This would make it possible to determine the thickness of foam that would be needed for a landmine blast to reduce the loads transmitted to the leg to a tolerable limit. This evaluation will be done by performing dynamic loading of the different foams at different velocities.

A criticism of the literature that has studied the effect of blast on different boots before was the lack of standardisation of the variables involved in the testing process that made the results incomparable between the different studies. All of the studies (Fujinaka et al, 1966; Lans, 1999; Harris et al, 2000; Bergeron et al, 2006; Van der Horst et al, 2008; Nicol, 2011) conclude that commercial boots are not able to offer adequate protection against even a small mine. This was applicable to most of the anti – personnel mine boots as well, while the boots that do offer protection still resulted in severe damage to the heel. Additionally, the majority of the boots tested in literature that claim to be mine resistant failed to match the claim, highlighting the lack of a robust testing method. This combined with the fact that blast testing is an expensive and time consuming process with results that are sensitive to small changes requires the development of a new test method that is able to address all of these issues. This requires first conducting blast tests against commercially available boots to get a base line for the loads and impulse data so that the blast tests can be quantified. The commercial boots should be those that are widely used by military personnel and should have different constructions. The variables for the blast test will be determined based on the previous work done on the literature. Following this the new test method will be developed that will aim to meet the performance of the blast test in terms of the total impulse measurements and the damage observed, while being cheaper and faster to perform. This will be done by developing a new gun based test that is able to shoot sand at the target at high velocities to achieve the loads and the impulse measurements while being able to achieve penetration to perform an evaluation of the contamination effects.

The review of the literature (Bass et al, 2004; Van der Horst et al, 2008; Nicol, 2011) has shown that boot damage alone cannot be used a predictor of the damage to the leg; additional assessment is required is the form of evaluation of tissue damage. The literature (Harris et al, 2000; Bergeron et al, 2006) has shown that a number of surrogates have been tried and tested, and while some of them are well calibrated and match the performance of a human leg, they have a few issues. These range from ethical restrictions to cost of the simulant per trial due to the destructive nature. Hence, a simpler simulant like gelatine is ideal since it is both reliable and reproducible and is able to capture the damage that is produced which can be compared. A final consideration is the method that will be used to characterise and compare the damage that is produced. While a few have been explored in the literature (Fujinaka et al, 1966; Mah et al, 2007), they are applicable only under certain scenarios and is dependent on the condition that the surrogate remains intact. Hence, the final decision on this will be taken as the surrogates are being evaluated.

While the literature (Bergeron et al, 2006) has shown that some work has been done into looking at evaluating the performance of over boots, these have been directed at reducing the damage to the leg in terms of the loads and energy transmitted. The literature (Rountree et al, 2000; Trimble et al, 2001) has identified contamination as one of the factors that determines the surgical outcome post blast. Contamination protection from mine blasts requires the evaluation of protective equipment such as socks that are already worn and how they are able to affect it. This will be done using the new gun based test method that will be developed as part of this thesis.

The work presented in this thesis will aim to determine the effects that different foam densities and thickness will have on the loads and total impulse measured. An initial investigation will be conducted using blast tests to determine the protection offered by commercially available boots while getting base line data for the loads and total impulse which will be used to develop the new test method. The new test method will be validated against the blast test and will be used to study the contamination effects and the protection offered by socks.

Chapter 3: EFFECT OF FOAMS ON LOADS MEASURED

3.1 Introduction

As was discussed in chapter 2, it has been suggested in the literature (Avalle et al, 2001; Mah et al, 2007) that foams can be used as a means to reduce the loads transferred to the leg during the blast. This is usually done by means of increasing the standoff distance, which in the case of foams means using high thickness foams in the sole of the boots. The literature (Muschek et al, 1997; Mah et al, 2007) shows that increasing the standoff distance is the easiest way to decrease the loads transferred to the leg, which is used in combination with other mechanisms to make AP mine boots. However, as mentioned in chapter 2, Fujinaka et al. (1966) says load to the leg is not the criteria that determines damage but rather the total impulse and impulse per unit area that is the important criteria.

This chapter discusses the work that was undertaken to determine the effectiveness of a family of conventional polymeric foams by evaluating their performance in terms of ability to reduce the loads transferred in addition to the ability to affect the total impulse transferred. This was done by using a drop tower to compress a sample of foam and record the loads at both the striker and the anvil. The effect that the thickness of the foam has on the loads and the total impulse was studied by using the same foams that was stacked in varying number of layers. The foams were struck at different velocities, to study the effect that the velocity has on the loads and the total impulse produced.

3.2 Materials and methods

3.2.1 Test rig

The test rig used was an Imatek[1] IM10 Impact Test System which was equipped with a striker (2.7kg) and an anvil that had a load washer attached to both of them to record the loads at both the striker and the anvil. The load washer that was used for the striker was a Kistler[2] 9031A connected to a type 5017 charge amplifier which was calibrated for 60kN and connected to a Imatek c3008 data acquisition system. For the anvil another 9031A load washer was used was calibrated for 60kN and was connected to the c3008 data acquisition system directly. The Imatek c3008 data acquisition system was connected to the desktop where the data was recorded in ImpacqtV3 software.

[1] Imatek Ltd, Old Knebworth, Hertfordshire United Kingdom.
[2] Kistler Instruments Ltd., Hampshire, United Kingdom.

3.2.2 Foam

For the trials 3 different foam types were used having three different densities i) HD 115 (115Kg/m^3) ii) HD 80 (80Kg/m^3) and iii) LD 45 (45Kg/m^3) (Appendix D). The foam sheets of nominally 10mm thickness were cut into 50mm discs that were mounted to the anvil either as a single layer or layers going up to 5 layers (table 3.1).

Table 3.1: Foams used for impact testing and the number of layers used

Foam	Density (kg/m^3)	Number of layers	Thickness of layers (mm)
HD 115	115	1	9.8
		2	19.5
		5	48.8
HD 80	80	1	10.6
		2	21.1
		5	52.9
LD 45	45	1	9.4
		2	18.8
		5	47.0

3.3 Preliminary test setup and method

The different foam samples were attached to the anvil using a piece of adhesive tape and were struck by the striker at a fixed velocity. The samples were then struck again at the same velocity to determine if there was any difference in performance between new uncrushed foam and foam that was crushed previously (table 3.2). The data from the load washers for each of the trials was recorded on the desktop using the ImpacqtV3 software.

The impact events were recorded using a Phantom high – speed video camera (V12[1]) (10000 fps, 6μs exposure time and 1280 x 480 resolution) with the target illuminated from the side and the back using two LED lights. Each file was calibrated by using a known length visible in the image; converting pixels in the image to a dimension in mm and analysed using Phantom software (Vision Research, Phantom Camera Control Application 2.6). Once calibrated it was possible to perform additional calculations such as displacement (crush) and the velocity at which it crushed.

Table 3.2: Test variables used for impact testing foams

Foam targets	HD 115, HD 80, LD 45
Number of layers	1 layer, 2 layers, 5 layers for each type of foam (3 repeats of each + 3 repeats on the same foam after being crushed)
Velocity	1m/s, 2m/s, 5m/s for each of the layer type for each of the foam type
Load cell	Striker: 9031A via type 5017 charge amplifier connected to IMATEK c3008 data acquisition system; Anvil: 9031A connected to IMATEK c3008 data acquisition system

3.4 Results and discussion

To make sure that the properties of the samples remained the same within a particular foam density, the thickness of 10 random samples was measured. The hardness of each of them was also measured using a Shore Hardness Durometer. Table 3.3 displays the average thickness and Hardness of each foam density, the entire data set is available in Appendix D. The hardness of HD 80 and HD 115 was close to the hardness of the foams used in the soles of commercially available boots such as the Lowa desert elite (Shore hardness – 70) and the Altberg MKII (Shore hardness – 45).

[1] Vision Research, Wayne, New Jersey, United States.

Table 3.3: Descriptive statistics of foams used with respect to average thickness and harness

Foam	Average thickness (mm)	Standard deviation (mm)	Average hardness	Standard deviation
HD 115	9.8	0.1	58	0.7
HD 80	10.6	0.2	44	0.7
LD 45	9.4	0.2	18	0.8

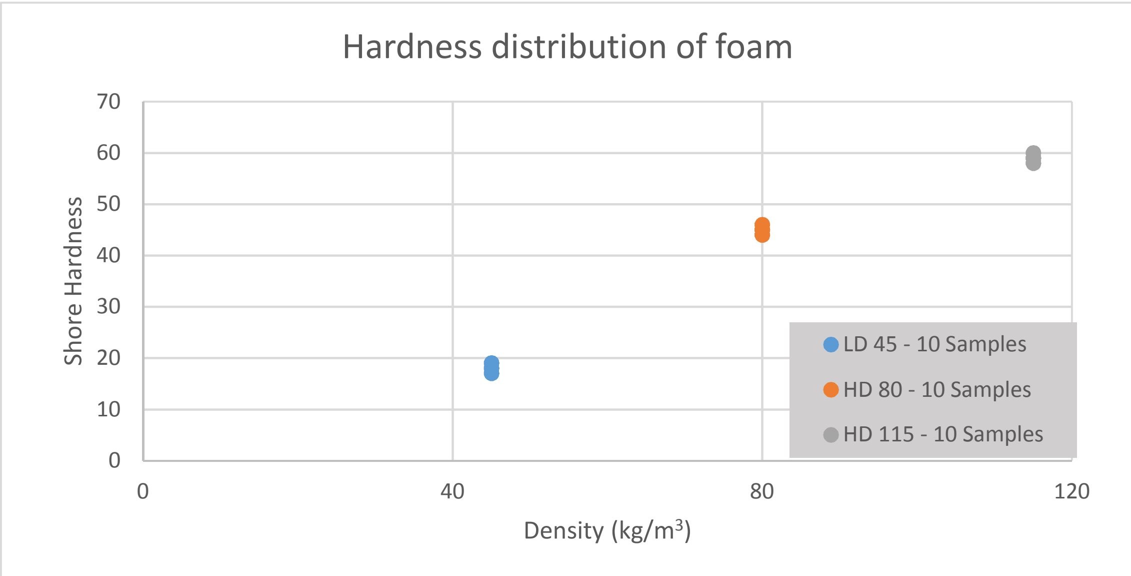


Figure 3.1: Hardness distribution of three different densities of foam

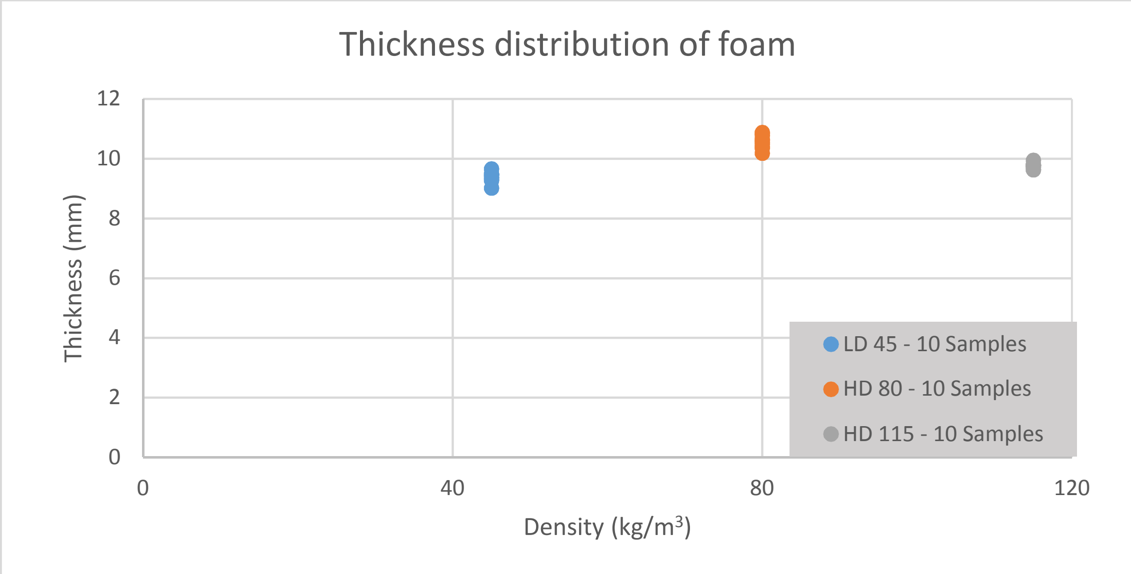


Figure 3.2: Thickness distribution of three different densities of foam

The results show that the thickness and the hardness of the foam samples for each density remained consistent throughout (figure 3.1 and figure 3.2). The above figures show that for 10 samples of each foam the thickness and the hardness are quite closely grouped together without any outliers.

Appendix D shows the mean peak loads and the mean total impulse from the load washers at both the striker and anvil. The complete table showing the individual data for each of the foam, at different layers and velocities is in the Appendix D.

During testing it was observed that the loads recorded were quite high at a velocity of 5m/s for HD 115 and since the HD 80 and HD 45 have a lower density, testing was not performed at this velocity for 1 and 2 Layers due to fears of damaging the load cell.

Table 3.4: Force – Velocity – Layer relationship for HD 115 foam

Velocity/Layers	1 Layer	2 Layer	5 Layers	
1m/s	1.9	1.7	1.3	Loads measured on anvil (KN)
2m/s	1.9	1.8	1.8	
5m/s	17.4	4.1	2.1	

From the above table (table 3.4) it can generally be observed that increasing the number of the foam layers for a given velocity decreases the loads measured even if it is by a small factor. Additionally, it can also be observed that the loads measured are very similar to each other when the ratio of the velocity to foam layers is 1:1. This can be observed both on the striker and the anvil measurements. This makes sense since increasing the number of layers introduces more face interactions between the foam layers where the transfer of the loads is not perfect, moreover due to the increase in thickness it means that more energy is required to crush the cells in the foam before the load is transferred from the striker to the anvil, and hence a lower load is measured. This is supported by the testing conducted again using the same parameters but using the already pre – crushed foam. Since the foam has been crushed in the previous trials, the cells in the foam have already collapsed on themselves previously and will require lower amounts of energy during the consequent trials resulting in higher loads measured. This is supported by the results when comparing the data from un – crushed foam to the pre – crushed samples where the loads measured increases for the same velocity (table 3.5). Each of the foam was tested three times at the three different number of layers against the three different velocities. The total impulse was calculated from the force – time curve as the area under it. The values were averaged out for each foam density at each layer criteria against each velocity criteria.

Table 3.5: Load difference between for un – crushed and pre crushed foams for HD 115 at 5m/s

s.d. – Standard deviation

Layers	Mean striker force (kN)	s.d. (kN)	Mean anvil force (kN)	s.d. (kN)	Mean total impulse – striker (N.s)	s.d. (N.s)	Mean total impulse – anvil (N.s)	s.d. (N.s)
1 – New	17.4	0.3	15.8	0.2	19.3	0.1	17.5	0.1
1 – Used	31.8	0.5	28.4	0.5	22.7	0.2	20.0	0.2
2 – New	4.1	0.2	3.9	0.1	17.7	0.1	16.5	0.1
2 – Used	10.3	0.6	9.5	0.5	19.6	0.1	17.9	0.1
5 – New	2.1	0.1	1.9	0.1	18.1	0.3	16.8	0.1
5 – Used	2.2	0.1	2.0	0.1	19.0	0.2	17.7	0.1

Table 3.6: Analysis of variance for HD115 evaluating the effect of layers on the loads recorded at 5m/s

Layers	Load (kN)		Impulse (N.s)		N
	Mean (kN)	Standard deviation (kN)	Mean (N.s)	Standard deviation (N.s)	
1	17.4	0.3	17.5	0.1	3
2	4.1	0.2	16.5	0.1	3
5	2.1	0.1	16.8	0.1	3

A – Selected descriptive statistics

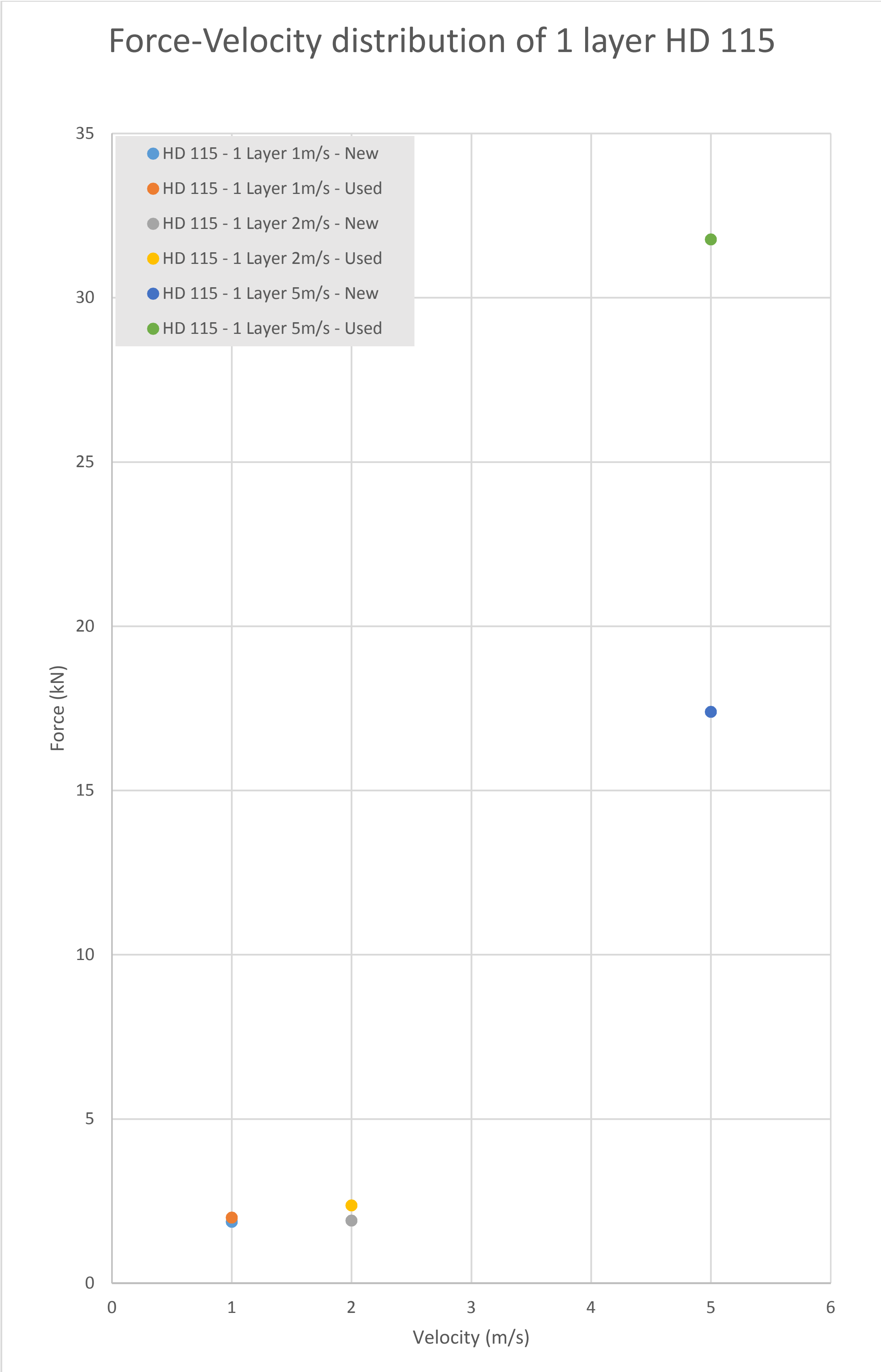
Source of variation	SS	d.f.	Mean square	F	Sig.	p≤
Load	414.98	2	207.49	6206.08	0.0001	0.0001
Error	0.20	6	0.033			

B – Analysis of variance for loads recorded

Source of variation	SS	d.f.	Mean square	F	Sig.	p≤
Impulse	1.58	2	0.79	98.75	0.0001	0.0001
Error	0.05	6	0.008			

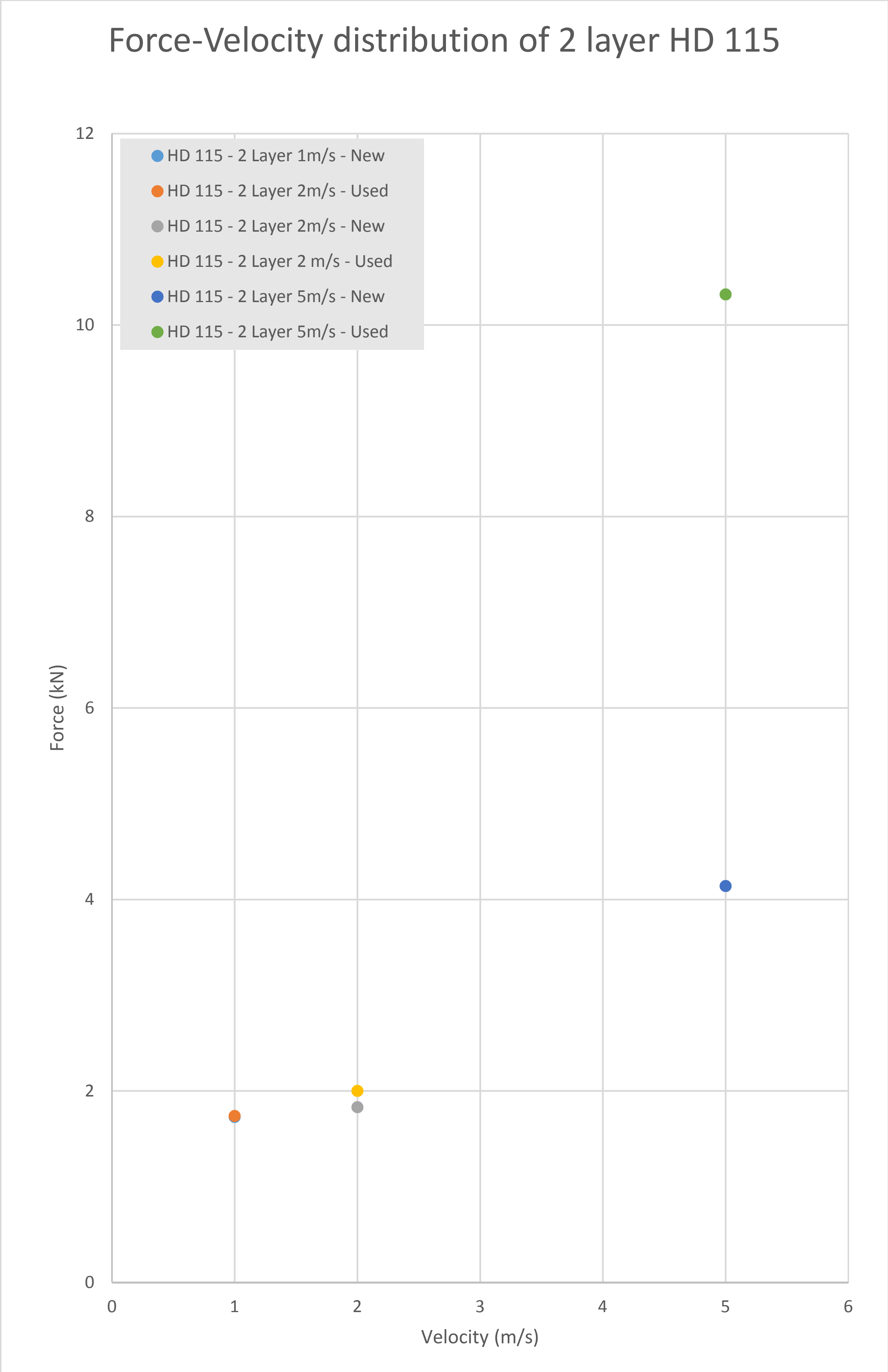
C – Analysis of variance for impulse recorded

Analysis of variance was used to determine if the number of layers had significant effect on the loads and impulse recorded. The number of layers had an extremely significant effect on the loads measured ($F_{2, 6}$ = 6206.08, p≤0.0001) (table 3.6B). This is reflected in the difference in the loads measured between the different layers. The number of layers also had an extremely significant effect on the impulse measured ($F_{2, 6}$ = 98.75, p≤0.0001) (table 3.6C). However, the magnitude of the impulse between the different layers does not reflect the effect the layers have on the impulse recorded.

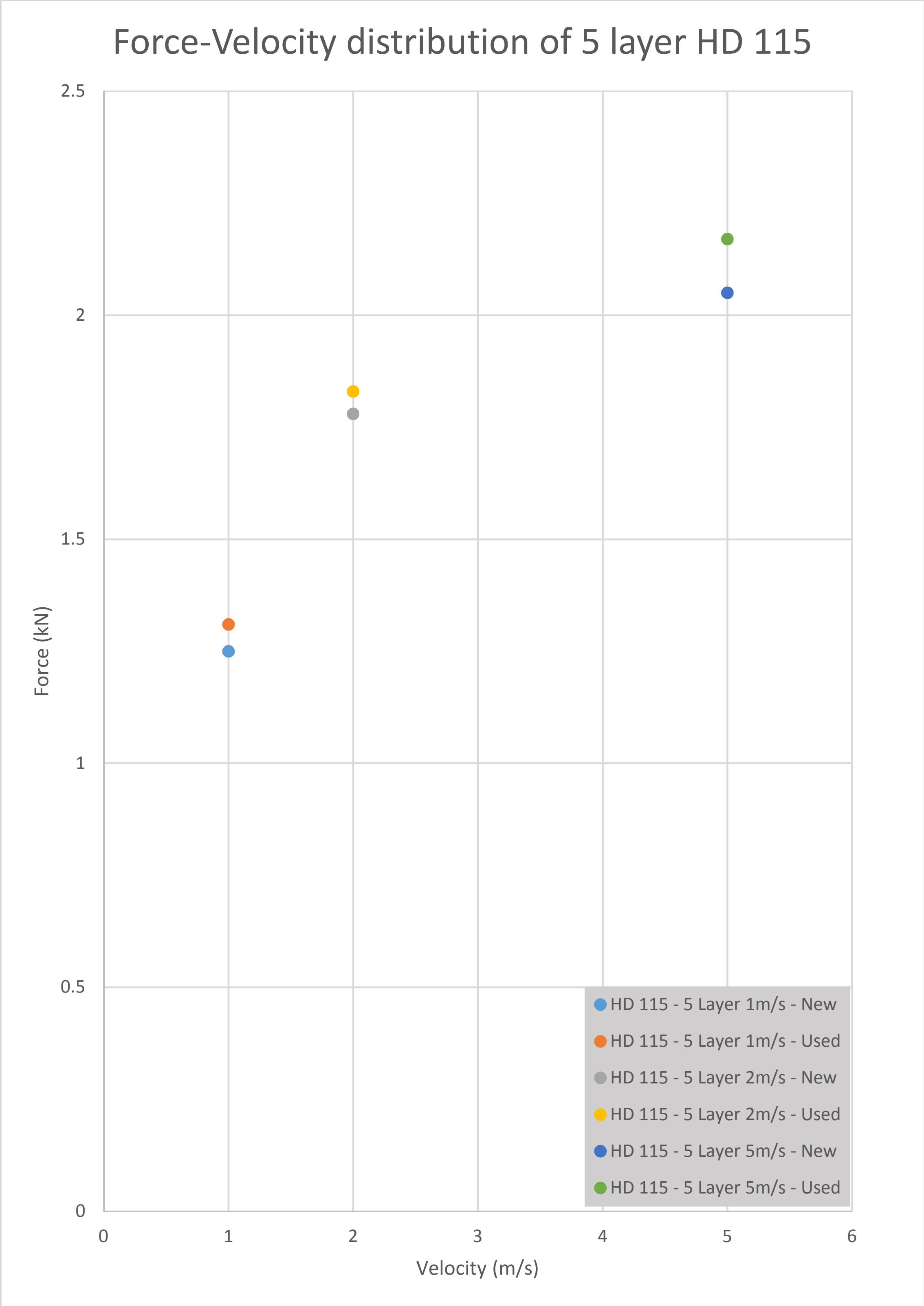


Force-Velocity distribution of 1 layer HD 115
HD 115 - 1 Layer 1m/s - New
HD 115 - 1 Layer 1m/s - Used
HD 115 - 1 Layer 2m/s - New
HD 115 - 1 Layer 2m/s - Used
HD 115 - 1 Layer 5m/s - New
HD 115 - 1 Layer 5m/s - Used
35
30
25
20
15
10
5
0
Force (kN)
0
1
2
3
4
5
6
Velocity (m/s)

A


Force-Velocity distribution of 2 layer HD 115
HD 115 - 2 Layer 1m/s - New
HD 115 - 2 Layer 2m/s - Used
HD 115 - 2 Layer 2m/s - New
HD 115 - 2 Layer 2 m/s - Used
HD 115 - 2 Layer 5m/s - New
HD 115 - 2 Layer 5m/s - Used
Force (kN)
Velocity (m/s)
0
2
4
6
8
10
12
0
1
2
3
4
5
6

B

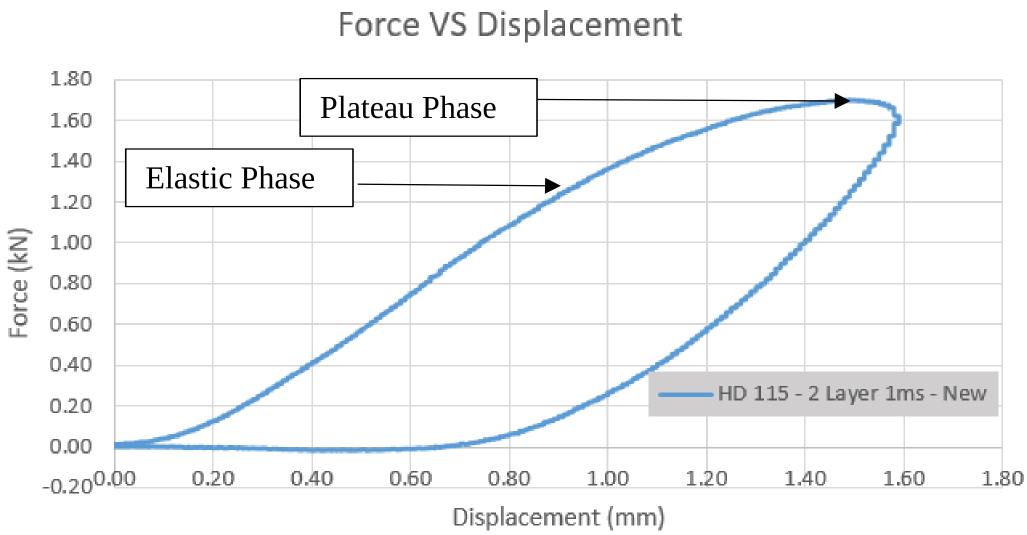


C

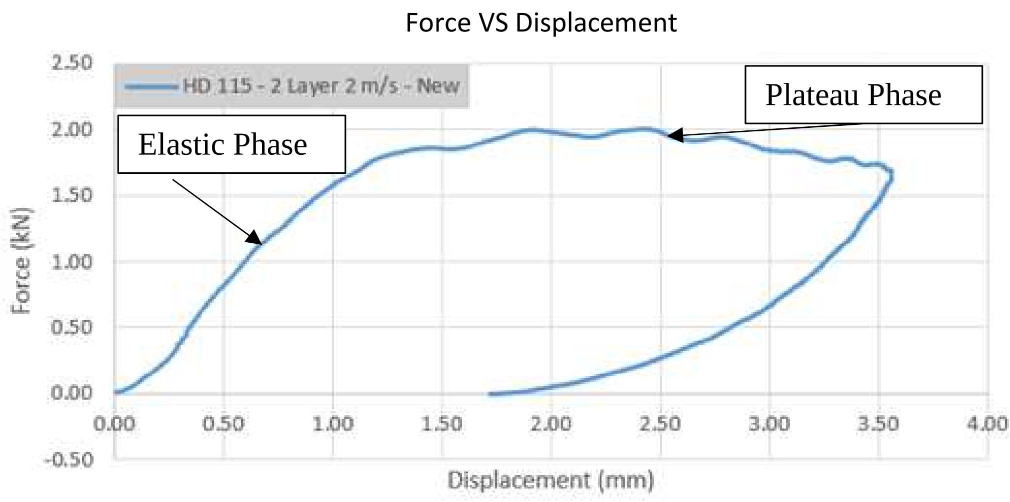
Figure 3.3: Force – velocity distribution of HD 115: A – 1 Layer; B – 2 Layer; C – 5 Layer

The graph (figure 3.3) clearly demonstrates that as the velocity increases the loads measured increases. In addition, it also shows that the loads measured generally decrease as the number of layers' increase. However, the loads measured increase for the same velocity when the same foam is repeatedly used.

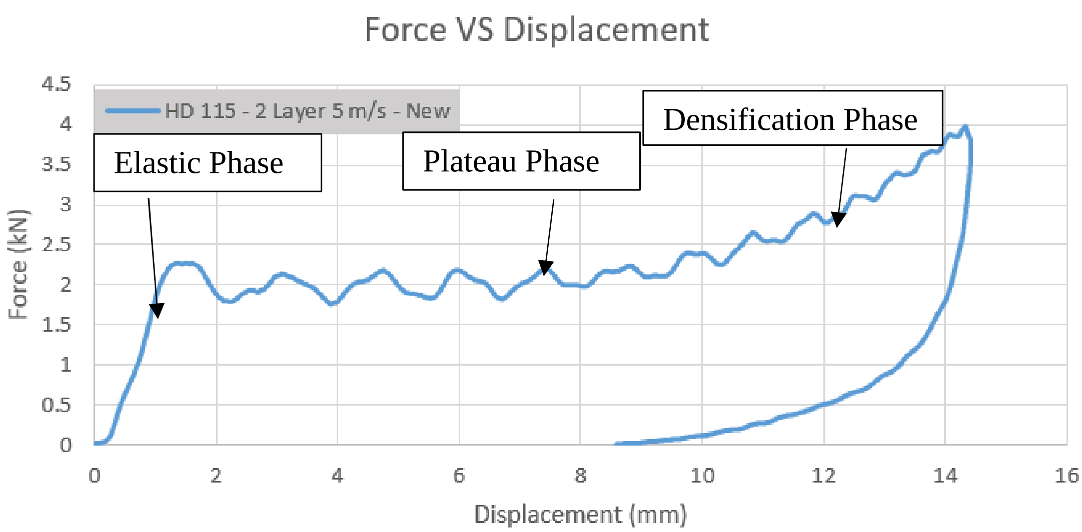
For all the foam tests the peak load is largely determined by how far along the stress strain curve the foam is pushed before the energy from the impact is used to crush the foam cells. Energy is used up by doing work on the foam so it is the area under the load displacement curve. For 1m/s (figure 3.4A) the load displacement curve doesn't progress beyond the elastic phase and the load stays the same, so adding layers has no effect. At 2m/s (figure 3.4B) the load displacement curve reaches the plateau phase but the energy is used up before it can reach the densification phase still resulting in low loads. However, when the foams are crushed at 5m/s the curve reaches the end of the plateau phase in the case of 5 layers (figure 3.4C) and goes into the densification phase when only 1 layer (figure 3.4D) is used. This results in a steep increase in loads measured which lines up with the literature.



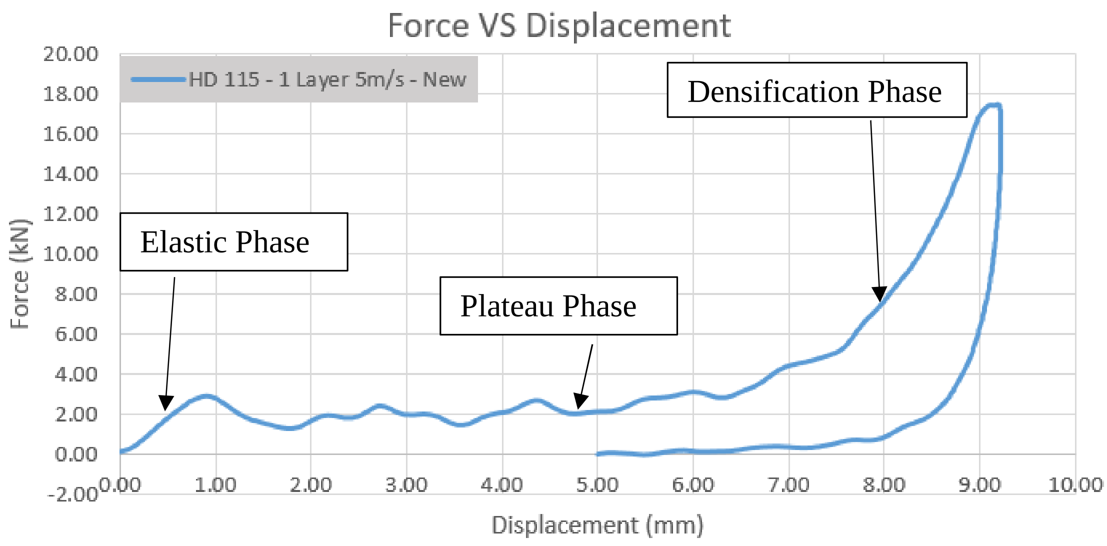
A


Force VS Displacement
HD 115 - 2 Layer 2 m/s - New
Elastic Phase
Plateau Phase
Force (kN)
Displacement (mm)
2.50
2.00
1.50
1.00
0.50
0.00
-0.50
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
4.00

B


Force VS Displacement
HD 115 - 2 Layer 5 m/s - New
Elastic Phase
Plateau Phase
Densification Phase
Force (kN)
Displacement (mm)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
2
4
6
8
10
12
14
16

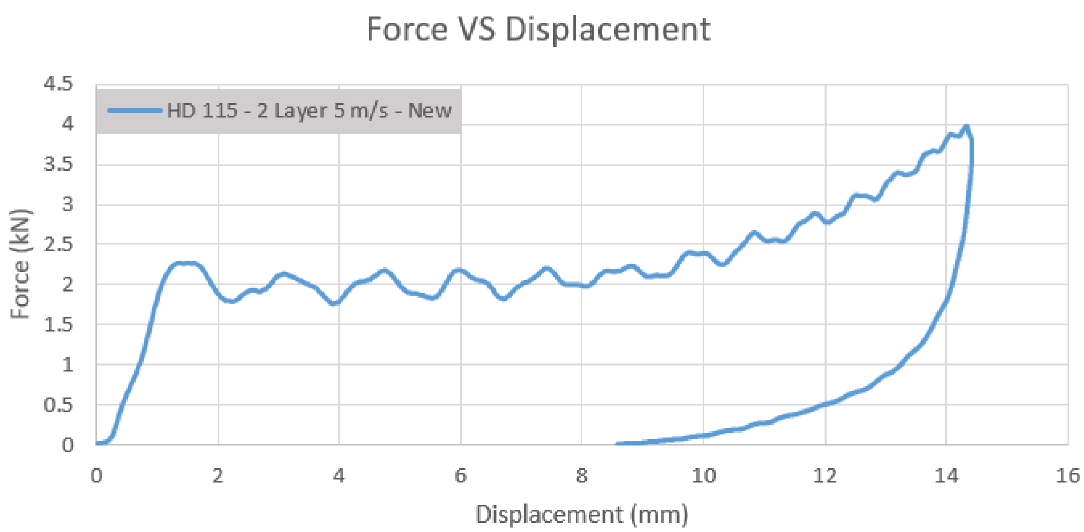
C



D

Figure 3.4: Force displacement curves of HD 115

Since the area under the curve determines the energy that is used up by the foam, when the pre – crushed foams are impacted again, since they are weaker they need to do more work to absorb the same amount of energy. However, since there is a limit on how displacement can occur, the loads must increase to do the same amount of work.



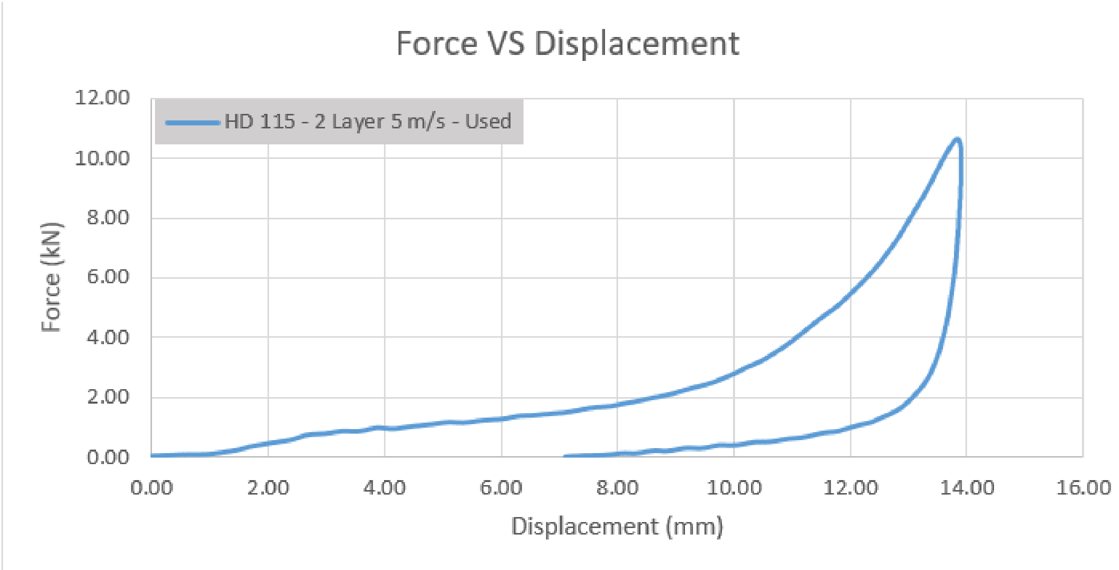


Figure 3.5: Force VS Displacement of HD 115 at 5m/s for new and pre – crushed sample

The literature (Muschek et al, 1997; Mah et al, 2007) states that increasing the standoff distance decreases the loads measured. In the case of the foam, this means increasing its thickness. As shown in figure 3.3, increasing the thickness of the foams decreases the magnitude of the load measured. However, the load measured at the striker and the anvil is quite similar to each other with only a minimal reduction in the loads measured at the anvil. For the data collected from HD 115 foam samples for 2 layers at different velocities, if the loads measured are compared for the un – crushed and pre – crushed foams, the data can be arranged as follows:

Table 3.7: Striker and anvil force measurements for 2 layers of HD 115 at different velocities

Velocity (m/s)	Layers	Mean striker force (kN)	Mean anvil force (kN)	% of striker force measured by anvil
1m/s	2 – New	1.7	1.6	93.6
	2 – Used	1.7	1.6	93.7
2m/s	2 – New	1.8	1.7	95.1
	2 – Used	2.0	1.9	92.5

5m/s	2 – New	4.1	3.9	94.2
	2 – Used	10.3	9.5	91.9

This table (table 3.7) demonstrates that foams that already have their cells crushed noticeably result in higher forces measured when the ratio of the velocity to the number of foam layers exceeds 1:1. The difference in the loads can be explained by the crushing of the foam cells as explained in the literature (Avalle et al, 2001). It can also be seen that the difference in the load measurement between the striker and the anvil is quite similar for the different velocities with the anvil measuring approximately 90% of the striker load. The table (table 3.7) also shows that pre – crushed transfer 90% of the striker load to the anvil.

As the striker strikes uncrushed foam, it compresses the foam at a particular velocity, causing the cell walls to collapse. When the test is repeated again on the same foam the striker compresses the foam at a higher velocity giving a higher value of deflection (figure 3.6). This results in a higher load measured and lower protection offered by the foam. This can be calculated from the high speed video of the foam as shown in table (table 3.7) for 2 layers of HD 115 foam.

Figure 3.6: 5 layer HD 115 at 5m/s (left to right): i) Starting point at trigger; ii) Foam at maximum deflection; iii) Pre – crushed foam used again at maximum displacement

Table 3.8: Displacement and velocity measurement for 2 layers of HD 115 new and pre – crushed foam

Striker velocity (m/s)	Foam	Displacement (mm)	Crush velocity (m/s)
2	New	3.2	1.1
	Used	4.6	1.5
	New	2.9	1.0
	Used	4.5	1.5
	New	3.4	1.1
	Used	4.1	1.3
5	New	14.6	2.8
	Used	14.9	3.7
	New	15.1	3.1
	Used	15.3	3.6
	New	14.7	3.1
	Used	15.4	3.7

Table 3.8 shows that the crush velocity (the velocity at which the anvil crushes the sample) increases as the velocity of the striker increases, but it also increases when the same foam is struck again. This is due to the cell structures in the foam already being collapsed, hence requiring lesser amount of energy to do so again (figure 3.7). No measurements were taken for 1 layer of foams for this trial since the displacement measurement was so minute that it was not possible to get a consistent result every time.

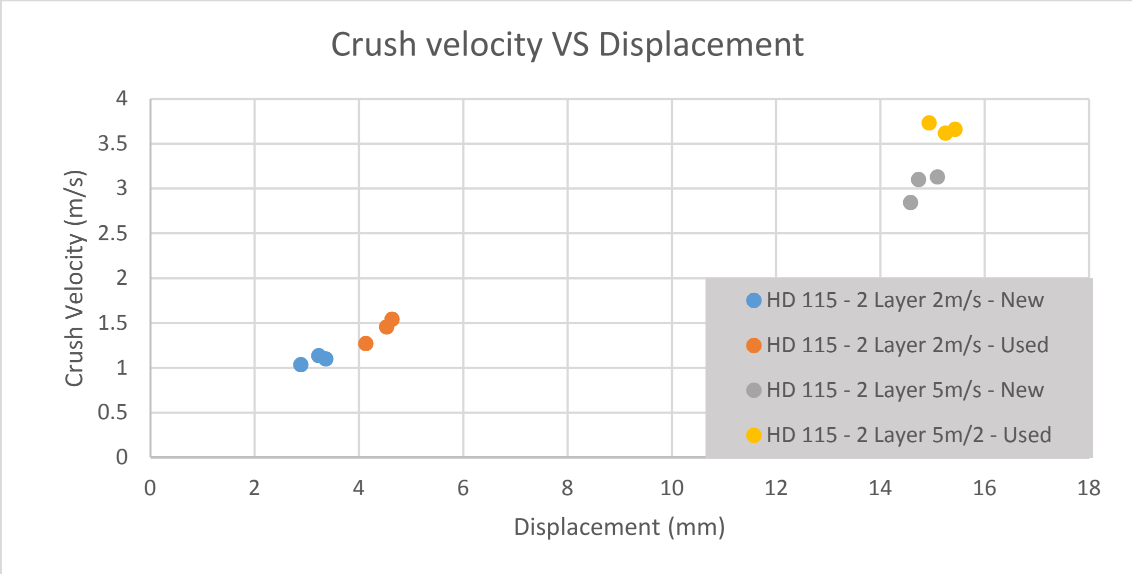


Figure 3.7: Crush velocity – displacement graph for 2 layer HD 115 at different velocities

For a normal solid material under compression, deformation will take place uniformly throughout the depth of the material. This is because the propagation velocity is greater than the loading velocity resulting in the loads being transmitted quicker than the deformation occurs. But for materials such as foam, the propagation velocity depends on the gradient of the stress strain curve. So for the elastic phase, the propagation velocity is relatively high whilst the plateau phase has slow propagation velocity since it lacks a slope. The densification phase due to the very steep slope, the propagation velocity is fast enough to keep ahead of the loading.

From the literature (Muschek et al, 1997; Mah et al, 2007) it was observed that increasing the standoff distance has been found to be the most effective way of minimizing the loads transferred to the leg, where doubling the standoff distance would halve the load transferred. In the testing conducted on the foams, a significant drop off in the loads measured was observed, this was however applicable to the trials conducted at the higher velocity where the ratio of the velocity to the foam layers exceeded 1:1 as it would have the necessary energy for the loads to be transferred and the observation to be made. This can be observed in table 3.9 for HD 115 foams.

Table 3.9: Load measurements for different layers of HD 115 foam at 5m/s

Velocity (m/s)	Layers	Mean striker force (kN)	Mean anvil force (kN)
5	1 – New	17.4	15.8
	1 – Used	31.8	28.4
	2 – New	4.1	3.9
	2 – Used	10.3	9.5
	5 – New	2.1	1.9
	5 – Used	2.2	2.0

The energy is known for a 20g PE4 blast test, which is discussed in further detail in chapter 4;

Energy, $E = 6.4KJ$

Energy/Area, $E/A = 289.1KJ/m^2$

Hence, for the drop tower to impart the same Energy/Area onto a 50mm foam disc, the velocity can be calculated;

Area of the foam disc, $A = 0.002m^2$

Energy, $E = 289.1 \times 0.002 = 0.578KJ$

Energy, $E = 0.5mv^2$

Where,

Mass of the striker, $m = 2.7Kg$

$v^2 = (578 \times 2)/2.7 = 428.2m^2/s^2$

$v = 20.7m/s$

The energy input to the foam is a function of velocity squared. From figure 3.4 and 3.5 it can be seen that the load increases sharply with an increase in displacement which might mean that it is a function of displacement squared. This means that the velocity to displacement ratio would be approximately 1:1 to keep the loads measured below 4kN. From the previous table (3.9), if the foams follow the same relationship between the layers and velocity, it can be seen that in order to keep the load at 4KN, which is lower than the fracture threshold of the leg, a layer to velocity ratio of 1:2.5 would be needed. This means that for the calculated velocity of 20.7m/s to produce the same energy per unit area on the foam you would need 8 layers of HD 115 foam which is approximately a HD 115 sole of 80mm thickness at minimum to limit the maximum load measured to 4KN. This value is quite similar to the thickness of the soles used in commercial platform sole anti – personnel mine boots (figure 3.8). This would be a very basic way to calculate the foam thickness required based on the data collected from the blast and the gun based test and doesn't take into account the nuances associated with a blast test and other complicated interactions. Moreover, it assumes that the entire sole is constructed out of a single piece of foam which is not how boot soles are generally constructed since they have technologies introduced into them to achieve the same protection using a sole of lower thickness.

Figure 3.8: Platform anti – personnel mine boot by Zeman®[1]

[1] Zeman Technogroup, Czech Republic.

If the same calculations are applied to the gun based tests, which is discussed in chapter 5 the following calculations can be made:

From previous calculation, the energy per unit area for the steel cylindrical case gun based tests is approximately, 4565.8KJ/m^2

Hence, for the drop tower to impart the same Energy/Area onto a 50mm foam disc, the velocity can be calculated;

Area of the foam disc, A = 0.002m^2

Energy, E = 4565.8 x 0.002 = 9.132KJ

Energy, E = 0.5mv^2

Where,

Mass of the striker, m = 2.7Kg

v^2 = (9132 x 2)/2.7 = 6564.4m^2/s^2

v = 82.2m/s

From the previous table (3.9), if the foams follow the same relationship between the layers and velocity, it can be seen that in order to keep the load at 4KN, which is lower than the fracture threshold of the leg you would need a layer to velocity ratio of 1:2.5. This means that for the calculated velocity of 82.2m/s to produce the same energy per unit area on the foam you would need 32 layers of HD 115 foam which is approximately a HD 115 sole of 320mm thickness at minimum to limit the maximum load measured to 4KN. This means a sole that is more than a foot high, which lines up with the previous points made, that in order to design a boot that completely protects against a blast you need a very large standoff distance even against a small charge. This makes it only practical to use such boots where there is a known threat.

However, Fujinaka et al. (1966) stated that it was not the load transferred that was the most important criteria that determines damage but rather the total impulse. From all the testing conducted on the foams it can be observed that for a particular foam density at a particular velocity when the number of foam layers are increased, although the loads measured decreases the total impulse remains the same or in some cases increases (Appendix

D). This is because when the number of foam layers increases, the peak load measured decreases and increases the time duration of that pressure peak. When this is considered from the perspective of a blast wave travelling through a boot, the event should be over as fast as possible since prolonging the event will mean more damage to the leg and the surrounding tissue (Wolf et al, 2009). Hence, increasing the standoff although it decreases the loads measure, is not the solution that is required unless mechanisms are introduced to reduce the total impulse which usually means introducing features into boots such as metal plates that can cause more damage to the leg when accelerated during the blast.

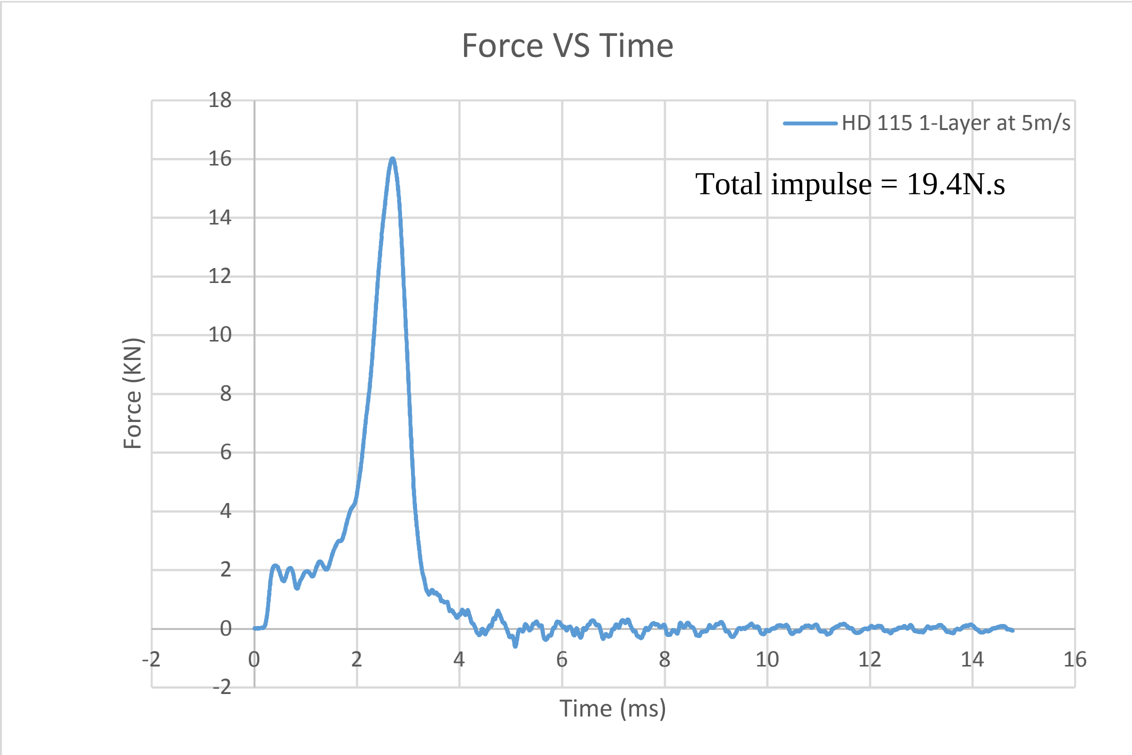


Figure 3.9: Force – time curve for 1 layer HD 115 at 5m/s

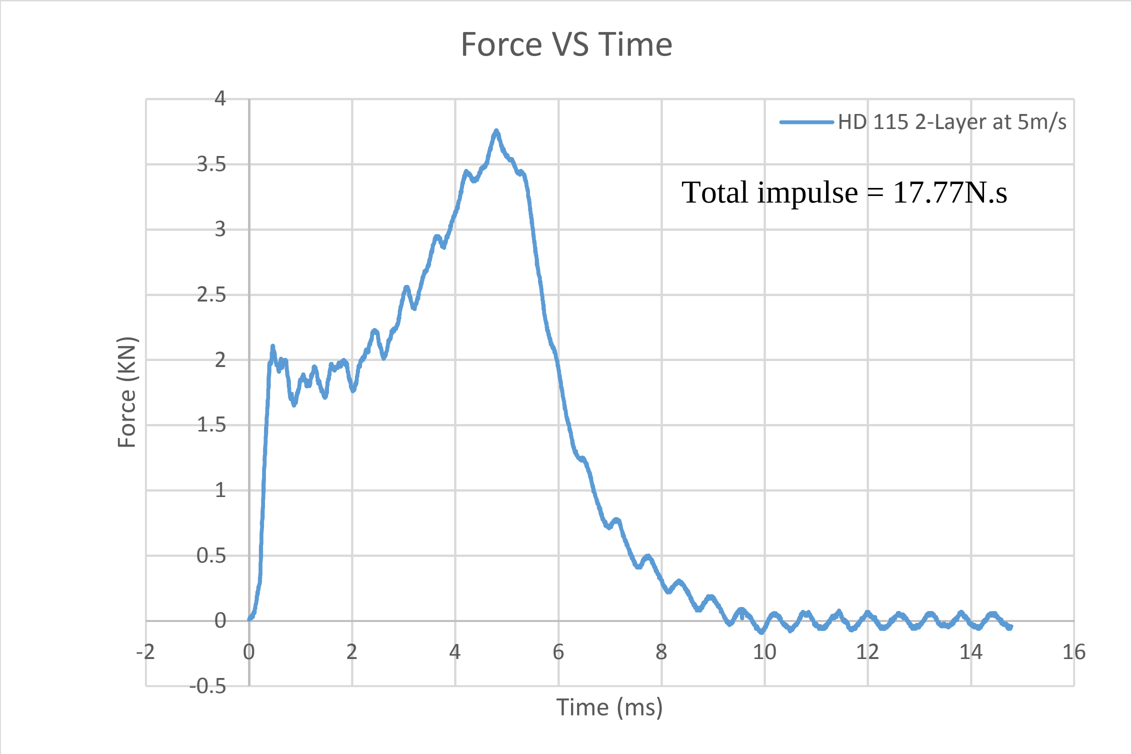


Figure 3.10: Force – time curve for 2 layer HD 115 at 5m/s

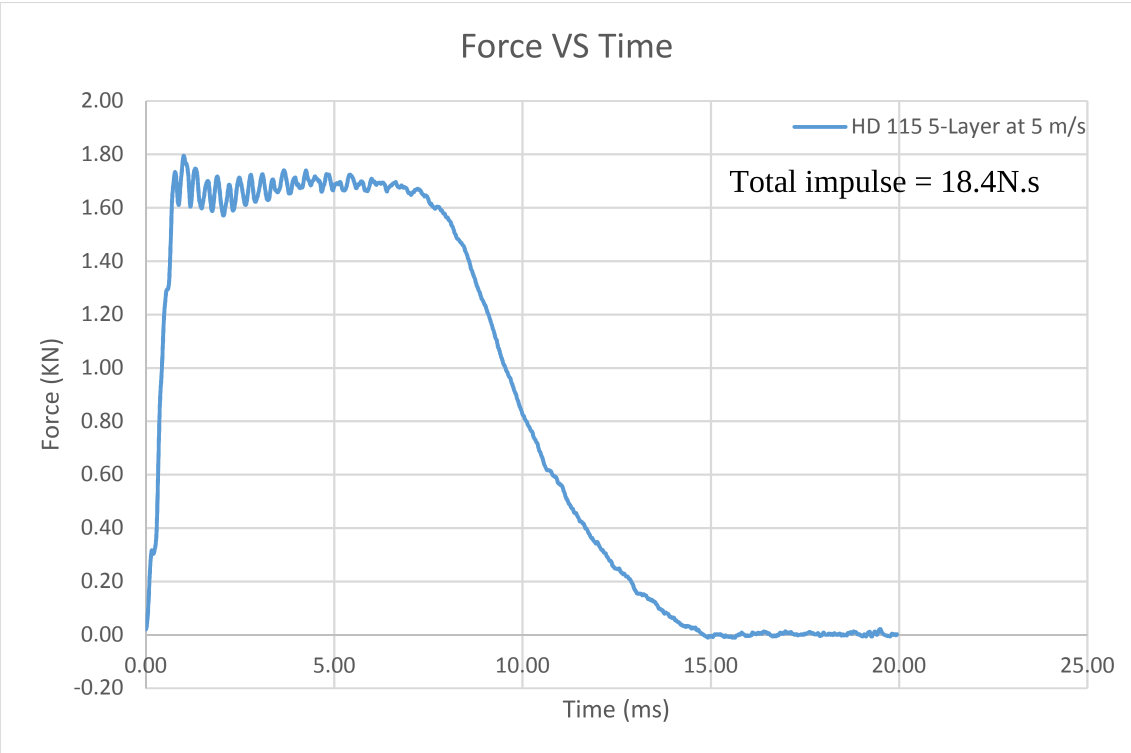


Figure 3.11: Force – time curve for 5 layer HD 115 at 5m/s

These graphs demonstrate the fact that the area under the curve (total impulse) does not vary by much as the thickness of the foam increases (1 Layer – 19.4N.s, 2 Layer –

17.7N.s, 5 Layer – 18.4N.s) for the given velocity despite the fact that the loads measured decrease (1 Layer – 17.5kN, 2 Layer – 4.24kN, 5 Layer – 1.99kN). In some cases, the total impulse increased for a given velocity as the number of layers increased (Appendix D). This lines up with the observations made in literature (Fujinaka et al, 1966) that it is not enough to decrease the loads transmitted; it is necessary to modify the total impulse. This means that reducing the loads might not necessarily reduce the damage to leg, resulting in significant damage during a blast event.

The following (figure 3.12) is the stress – strain curve for the HD 115 samples of 2 layers at 1, 2 and 5m/s. The testing of the other samples containing 1, 2 and 5 layers at 1, 2 and 5m/s follows the same curve demonstrating that the foams used are not strain rate sensitive for the regions that were observed during testing. The higher density of HD115 made it possible for it to be tested at all velocities at all the different foam layers. This is why the other densities are not shown below since it was not possible to test them at 1 and 2 layers at 5 m/s.

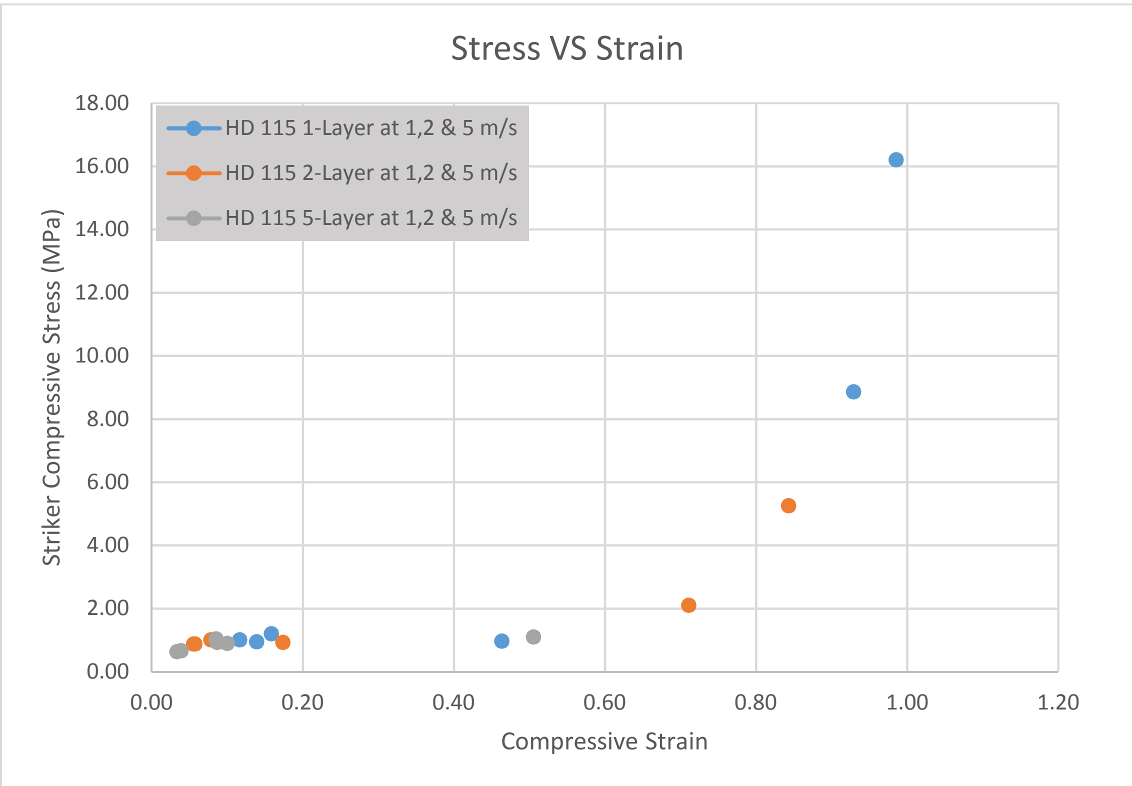


Figure 3.12: Stress – strain curve for HD 115 layers at different velocities

All of the observations made in this chapter with regards to HD 115 were also applicable to the other two foams used – HD 80 and LD45.

Chapter 4: BLAST TESTS

4.1 Introduction

As previously discussed frangible surrogate legs (Harris et al, 2000; Bergeron et al, 2006) have been used in literature to assess the performance of boots, however they are limited in terms of their cost and their ability to be used again. Metal surrogates (Lans, 1999; Van der Horst et al, 2008; Nicol, 2011) used in blast tests provide a relatively cheap test method to obtain baseline data on blast response. Hence, a series of blast tests were conducted using a metal surrogate system.

Chapter 4 discusses the work that was undertaken to obtain the baseline data for blast tests and to compare them with previous literature. This chapter is split into two parts: Part A – Blast tests using a metal surrogate, Part B – Blast tests using a gelatine limb as surrogate.

4.2 Part A – Blast tests using a metal surrogate

Part A describes the preliminary experiments designed to confirm results observed in the literature. The issue with blast tests has always been that it can be difficult to achieve good reproducibility, in addition to being expensive and time consuming. The purpose of this experiment was not to produce a large number of repeats to conduct a statistical analysis but to confirm the assumption that regular boots are not able to provide adequate protection against even a small charge when considering that the fracture threshold for the lower limb is 8.6kN.

Baseline data for the blast tests were recorded in the form of load and velocity data. Additionally, observations were regarding the damage to the boots which were categorised in accordance with the boot damage criteria (Bass et al, 2004).

4.2.1 Materials and methods

4.2.1.1 Test rig

The test rig used for these blast tests were based on modifications of the rig used by Nicol (2011). The rig used by Nicol consisted of a metal shaft with a 35kg weight that was allowed to moved vertically. The surrogate leg was attached to the shaft and the boot was mounted to it. The rig was lifted onto concrete blocks and secured in place using ratchet straps. The sand was contained in a hole that was dug into the ground under the leg (figure 4.1). The work identified a number of issues that came up during the testing. Since the shaft was only allowed vertical motion and the rig was already secured prior to placing the charge, this combined with the weight of the shaft meant that the task of placing the charge at the appropriate depth and then lowering the foot was quite difficult for the range officer tasked with the job. Since the sand was contained in a hole in the ground, it meant that the sand had to be shovelled after every trial in order to put fresh sand into the hole. Additionally, it also made it difficult to control the moisture of the sand since it meant that the sand was exposed to the atmosphere for a longer time.

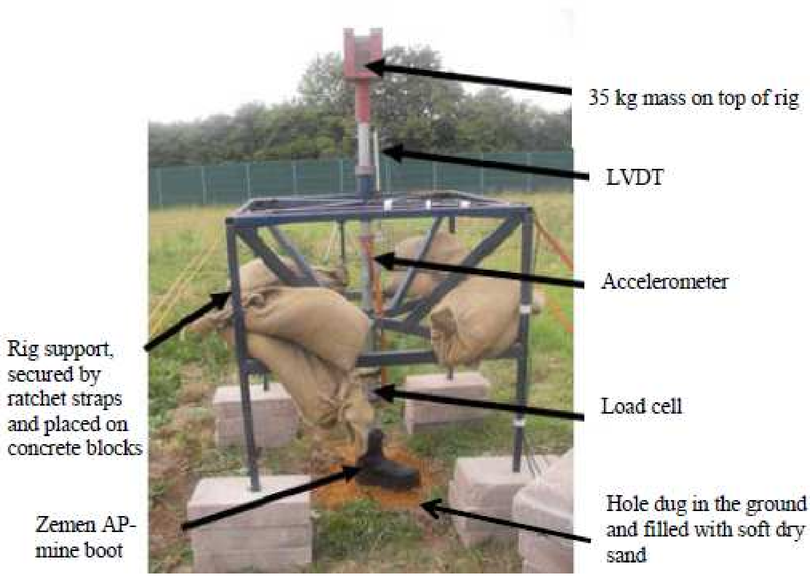


Figure 4.1: Test rig used by Nicol (2011)

Hence, a new rig was designed to address the issues that were observed by Nicol. The rig consists of a square metal shaft that was allowed to move freely through a square guide vertically. The shaft weighed 14kg in addition to which a mass of 30kg was attached to the top in the form of cylindrical discs giving it a combined weight of 45kg (figure 4.2).

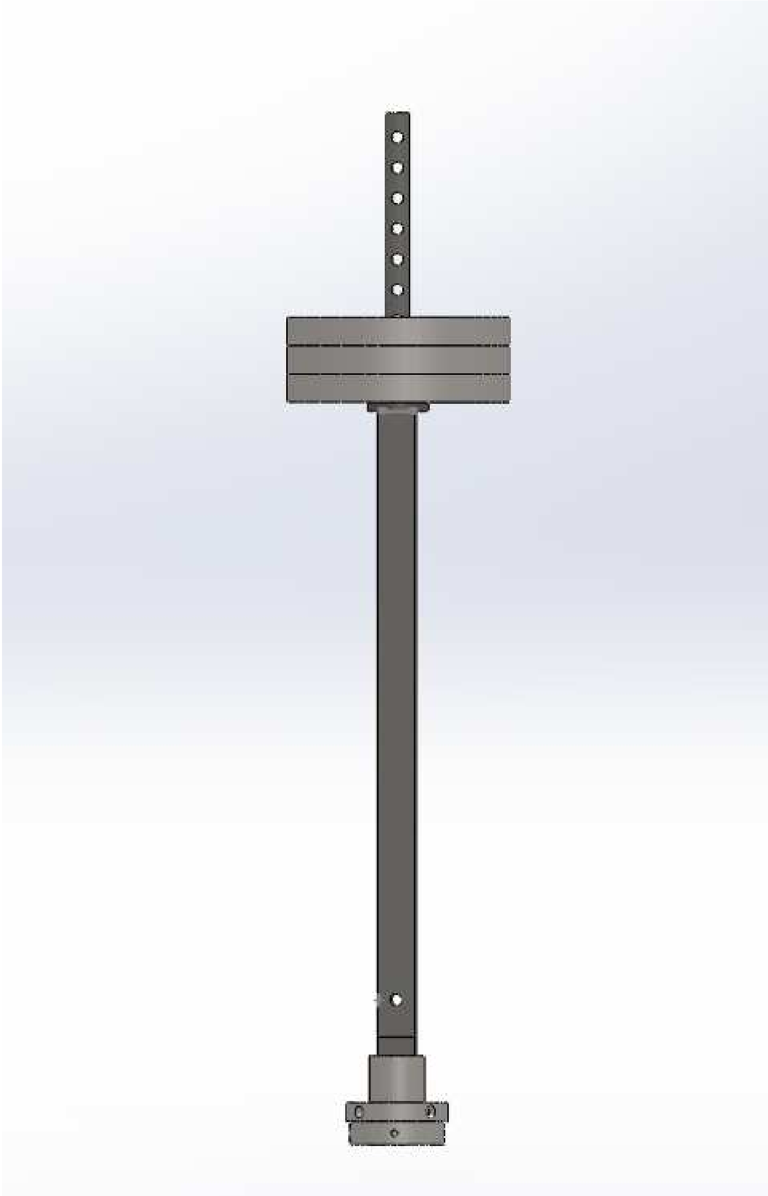


Figure 4.2: Square rig shaft with the 30 kg weights attached

The rig was designed such that it could be broken down into individual components and transported easily. In addition, a swivel mechanism was incorporated such that it makes the placement of the mine much easier and safer for the personnel handling the explosives during setup. Instead of the sand being filled into a hole in the ground, replaceable plastic trugs were used which made removal of the used sand easier and replacement much faster. The trug was enclosed in a thick steel cylinder to minimize the risk of fragments. Since trugs were used it meant that the sand could be preloaded into them in advance, this ensured that the moisture was tightly controlled and the sand was not unnecessarily exposed to the atmosphere (figure 4.3).

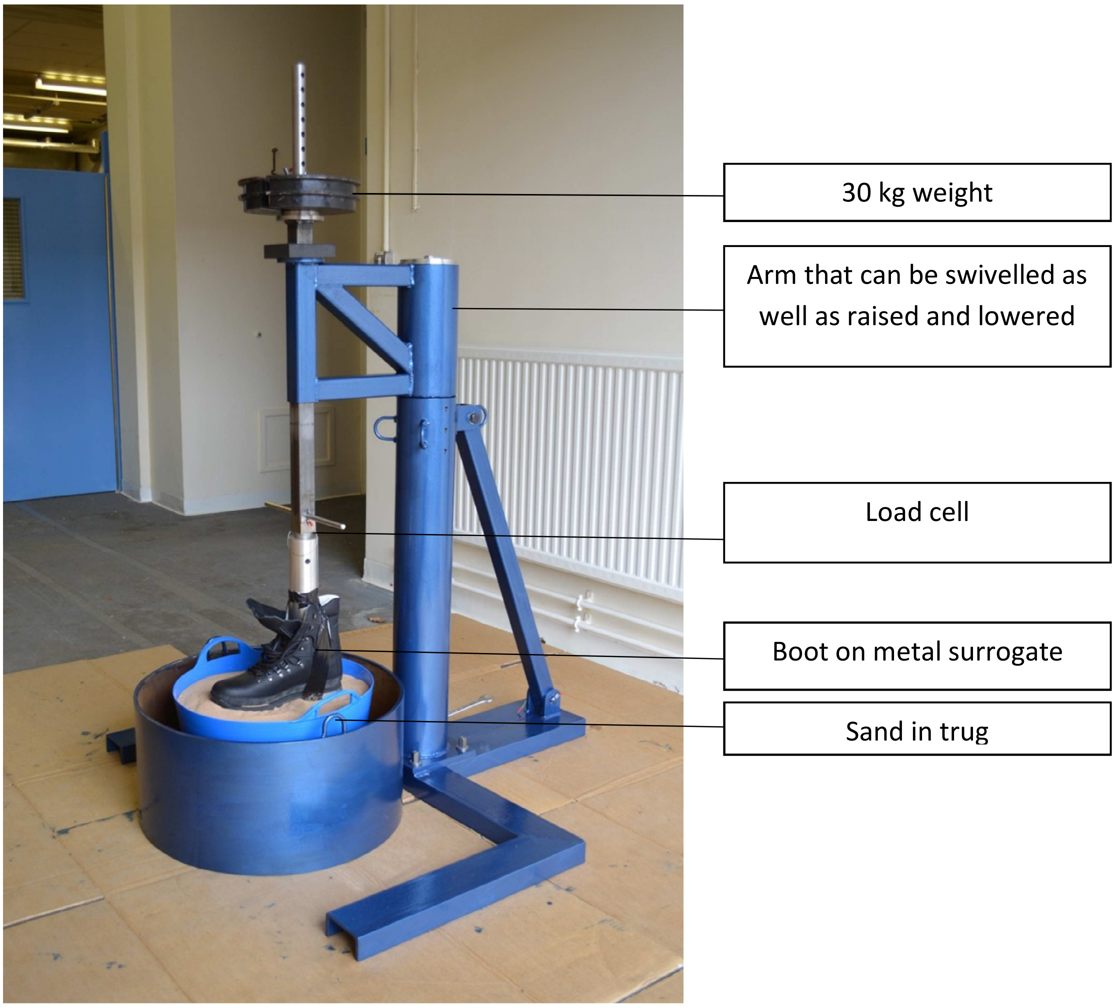


Figure 4.3: Detailed description of test rig used for blast testing

4.2.1.2 Surrogate

To simulate the lower limb a steel cylinder was used as the surrogate with the following dimensions 100x300mm and weighed 18kg. The surrogate was attached to the rig shaft by means of an m14 screw thread that was incorporated into the top of the surrogate. Although primitive, this ensured that there was a good transfer of the load to the load cell located above the surrogate and that additionally the surrogate was strong enough to be reused repetitively.

4.2.1.3 Boots

Three different boot types were used for the purpose of the experiment, all of which were a size 11 to ensure that the surrogate sits comfortably within the boots. The three boots used are as follows: A – Lowa[1] Desert Elite (LDE), B – Altberg[2] MKII (ALT), C – Old standard issue British combat boot or Assault boot (BCB).

4.2.1.3.1 Lowa Desert Elite (LDE)

The Lowa desert elites are tactical boots manufactured by LOWA who are a footwear manufacturer. This UK issued military boot is designed to endure the rigorous terrains of Afghanistan and have a special stud configuration to aid the roll – through/push off motion when on patrol and the softer rubber to provide additional comfort.

Construction:

Composition: Board lasted upper – cemented sole

Board lasted refers to the manner in which the upper is attached to the midsole, where board lasted means that the shoe has a firm board that provides a rigid platform for the foot. The upper is shaped around the board after which the sole is attached with an adhesive. The board in this shoe is made of plastic.

Upper: Suede leather + Cordura®

Cordura® is a brand of synthetic fabrics that have good durability and are resistant to abrasion, tears and scuffs. They are usually made of nylon, but may be blended with cotton or other natural fibres.

Lacing: Closed hooks

Lining: 3D mesh + Cambrelle®

Cambrelle® is a synthetic lining material used in boots meant for warmer conditions. It absorbs the moisture away from the foot in order to keep it dry and prevent blistering.

Sole: Vibram® MVS

[1] Lowa UK, Steeple Ashton, United Kingdom.
[2] Altberg, North Yorkshire, United Kingdom.

Vibram®[1] MVS is a rubber sole that is designed to provide boot stability and provide comfort. It uses a high hardness rubber compound that has a shore hardness of 70.

Upper height inside/outside: 165/210

Weight: 1550g/pair

Figure 4.4: Lowa desert elite (LDE) boot

[1] Vibram S.P.A, Albizzate, Italy.

Figure 4.5: Lowa desert elite (LDE) sole

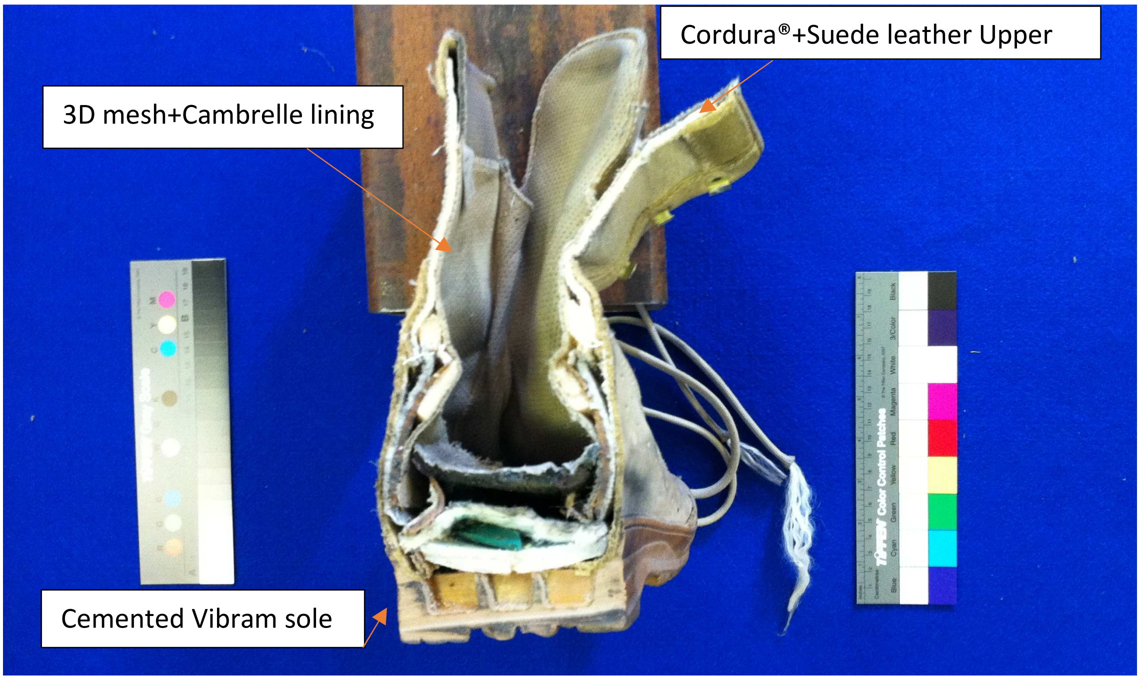


Figure 4.6: Cross – section of Lowa desert Elite

4.2.1.3.2 Altberg MKII (ALT)

The Altberg MKII is a combat boot designed by Altberg to be breathable with excellent drying out properties and to reduce the impacts on joints when running.

Construction:

Upper: Anfibio full grain leather

Anfibio leather is a full grain leather that has been treated to be waterproof. The leather is durable and is ideal for winter weather.

Lining: Cambrelle®[1]

Sole: Vibram® Masai and shock absorbing Microlite mid – layer

Vibram® Masai is a rubber sole that is designed to provide shock absorption and comfort. It uses a medium hardness rubber compound that has a shore hardness of 45. The Microlite mid – layer has foam rubber layers in between the sole that is designed to absorb shock while running and walking.

Weight: 800g (size 11)

Height: 23cm (size 11, including heel)

Figure 4.7: Altberg MKII (ALT) boot

[1] Camtex Fabrics Ltd. Cumbria, United Kingdom.

Figure 4.8: Altberg MKII (ALT) sole

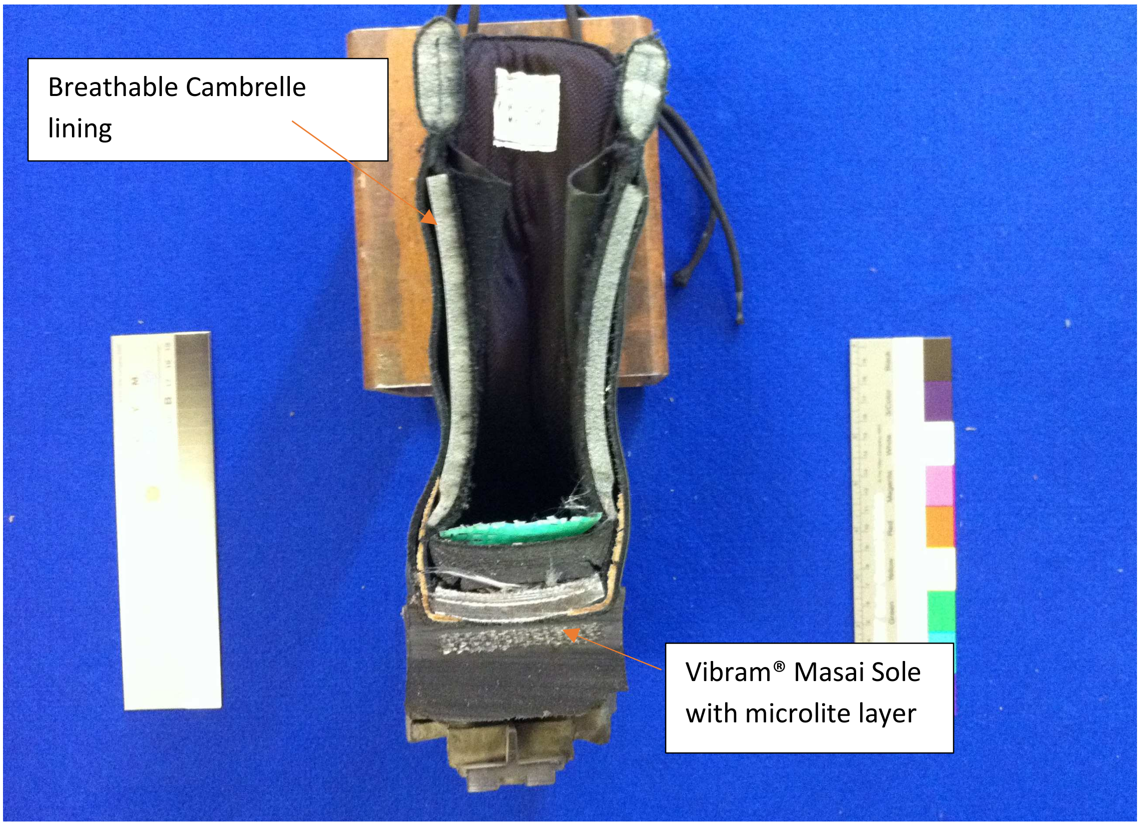


Figure 4.9: Cross – section of Altberg MKII

4.2.1.3.3 Old standard issue British combat boot or Assault boot (BCB)

This was the standard issue boot which are now replaced by brown boots.

Construction:

Leather: Water repellent high polish black leather

Upper: Leather upper with lined padded tongue; sewn in tongue to top and leather lined inner

Sole: Stitched vulcanised rubber with non – clog commando sole

Weight: 1000g (size 11)

Height: 21cm (size 11, including heel)

Figure 4.10: British combat boot (BCB)

Figure 4.11: British combat boot (BCB) sole

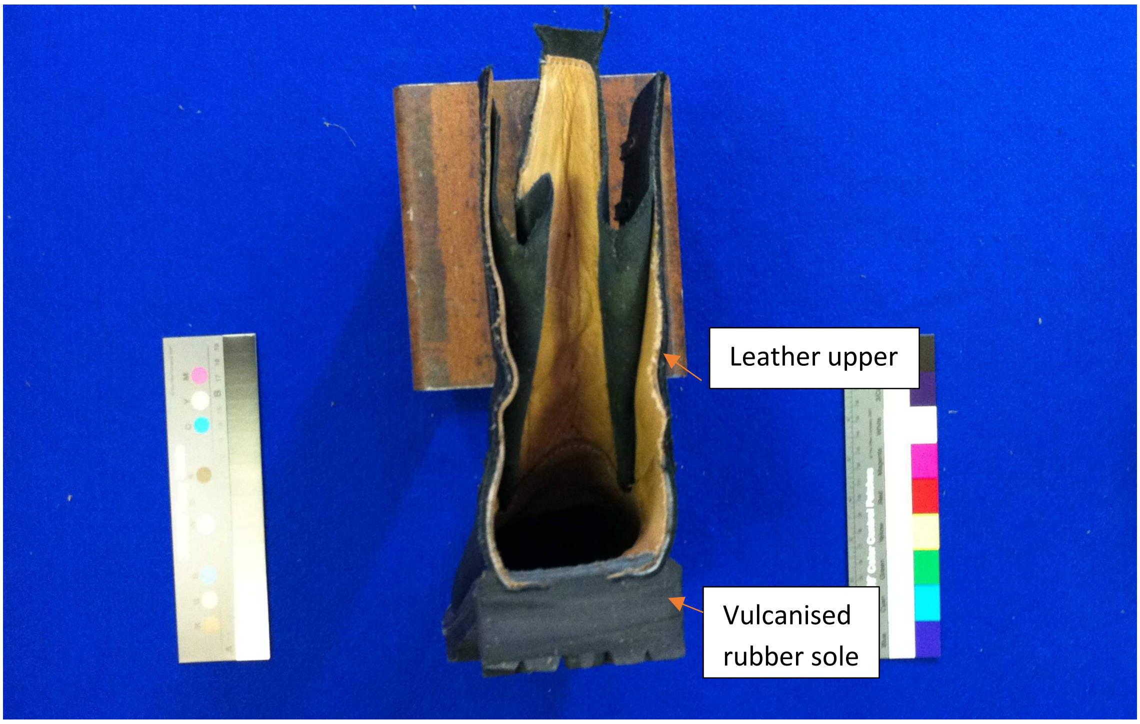


Figure 4.12: Cross – section of British combat boot

4.2.1.4 Sand

The sand used for the testing was plain playground grade silica sand with a particle size of 0.2 – 2mm in accordance with BSEN 1177 standard (1997). The sand was first dried on tarpaulins for a week to dry the sand as much as possible. It was then put in an environmental chamber in batches at 60^{o}C and 0% humidity for two hours each. The sand was then sieved using a Rotary Soil Sieve having a mesh size of 2.5cm x 1.5cm to get rid of any gravel or rocks if present; this was done to meet the safety requirement of the explosive range to ensure that no potential fragments were present. The sieved sand was then shovelled into plastic trugs. For experiments requiring 5% moisture content; after the sand was dried and sieved the appropriate quantity of water was added to the batches and then mixed before shovelling.

4.2.1.5 Test method

The boot was placed on the end of the leg and secured. The load cell (Kistler 9051A) was attached and connected to the computer. Trugs containing sand filled to the brim were placed beneath the rig. The centre of the heel was estimated by lowering the boots such that it was flush with the sand. A plastic tube was pushed into the sand such that it surrounded the centre of the heel perfectly until it was flush with the sand. The sand was then excavated from the inside of the tube to enable easier placement of the charge. When satisfied that no more adjustments had to be carried out; a 20g charge of PE4 was placed at a depth of 60mm after which it was carefully re – covered with sand. A 30kg mass was added to the top of the rig in the form of static weights and the leg carefully lowered until the boot was resting just above the sand, placing no load on the sand. After the blast, the trug if in one piece was lifted out of the steel cylinder, if not it had to be shovelled out.

The blast events were recorded using a Phantom high – speed video camera (V12) (29000 fps, 5µs exposure time and 256 x 600 resolution). A scale was used in all blast tests to allow the high – speed video footage to be calibrated. The loads were measured using a Kistler 9051A load cell (range 0 – 120kN) and Impacqt V3.0 software running on an Imatek C3008 data capture system.

Having noted and saved copies of the computer data, the boot was replaced on the leg and the procedure repeated. The procedure was later repeated using sand with a 5% moisture content to see if these changes produced results that were observed in literature.

4.2.1.6 Blast test analysis

At the site post – blast, the degree of boot damage was catalogued, photographs of the boot remains was taken and collected and the video stopped and checked. The computer data was checked to determine load while the acceleration was determined post trials from the high speed video. The degree of damage was categorised using the criteria set up by Bass et al. (2004).

4.2.1.7 Boot damage analysis

Each of the boots was physically examined post blast to determine the degree of damage sustained. These were then categorised according to the boot damage criteria that was developed by Bass et al. (2004).

Table 4.1: Boot damage criteria (Bass et al, 2004)

Boot damage level	Description of damage level
BD1	Minor damage to boot (i.e. portion of sole blown off, insole destruction)
BD2	Structural damage to boot (i.e. minor blast penetration into foot compartment of boot)
BD3	Breach (i.e. massive blast penetration into foot compartment of boot)

4.2.1.8 Load and impulse measurements

All of the blast tests were conducted using a Kistler 9051A (figure 4.13) (Appendix C) load washer connected to a Kistler type 5017B (figure 4.14) multichannel charge amplifier with the data being recorded in ImpacqtV3 software. The force with respect to time was recorded in software at 8000 data points over a period of 50ms from which the peak force was measured. This data was then exported to an excel spread sheet to carry out further calculations and analysis. The total impulse was calculated from the force data.

Figure 4.13: Kistler 9051A load washer

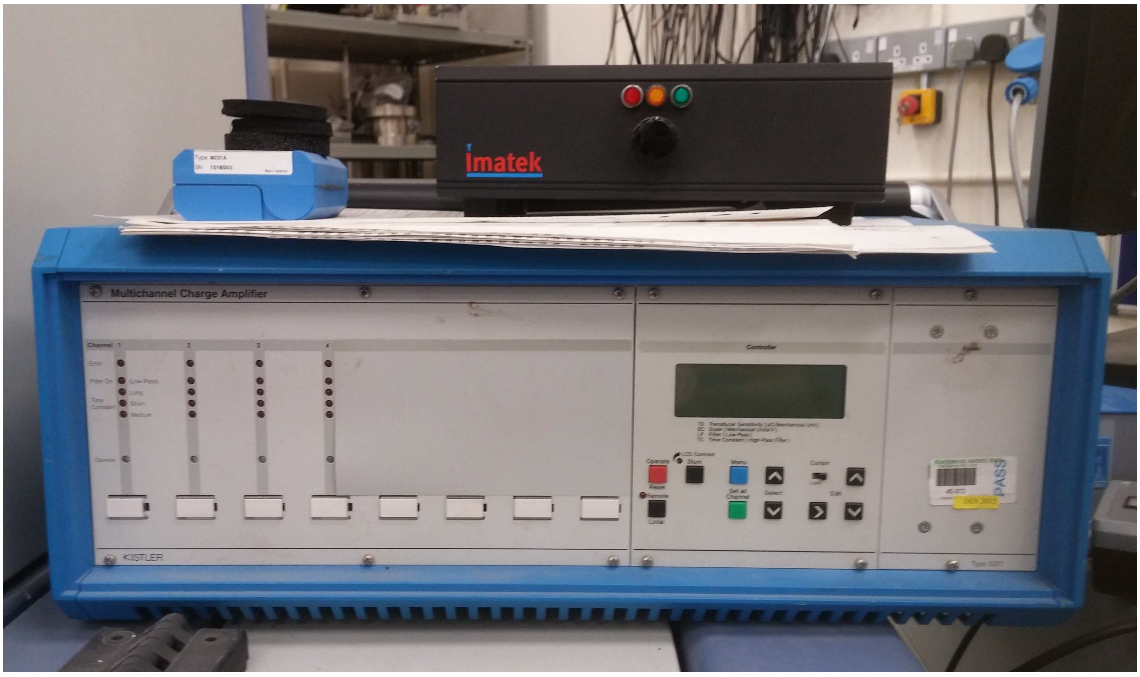


Figure 4.14: Kistler 5017B charge amplifier

Table 4.2: Blast test variables for metal surrogate

Burial depth (mm)	60
Charge weight (g)	20
Target	Lowa desert elite (LDE), Altberg MKII (ALT), British combat boot (BCB)
Sand	Dry, Wet (5% moisture)
Load cell	9051A load washer via type 5017B charge amplifier connected to IMATEK c3008 data acquisition system

4.2.2 Results and discussion

Table 4.3 displays the result of a 20g charge of PE4 at 60mm depth against three different types of boots using two different soil conditions.

Table 4.3: Results of blast test for 20g PE4 at 60mm depth using metal surrogate

TI – Total impulse DL – Damage level D – Displacement

Firing	Boot	Soil	Peak force (kN)	Secondary peak force (kN)	TI (N.s)	DL	Displacement (mm)	Peak boot velocity (m/s)	Peak sand velocity (m/s)
1	LDE	Dry	125.7	17.8	175.5	BD1	14.1	1.6	59.5
2	LDE	Wet	113.1	25.7	212.1	BD3	19.3	1.2	53.5
3	ALT	Dry	96.3	24.4	133.8	BD3	21.9	1.1	65.5
4	ALT	Wet	125.7	35.2	184.6	BD3	12.2	1.2	62.1
5	BCB	Dry	103.7	39.9	145.9	BD3	13.5	1.0	70.4
6	BCB	Wet	–		–	BD3	10.6	1.1	53.6

From the experimental data of Lowa desert elites against 20g PE4 two sets of peaks are instantly observed in figure 4.15. It appears that the first peak is the transmission of the shock wave to the load cell and the secondary peak is actually the event where the boot gets crushed and the loads are being transferred. The literature doesn’t specify which of the two are of significance.

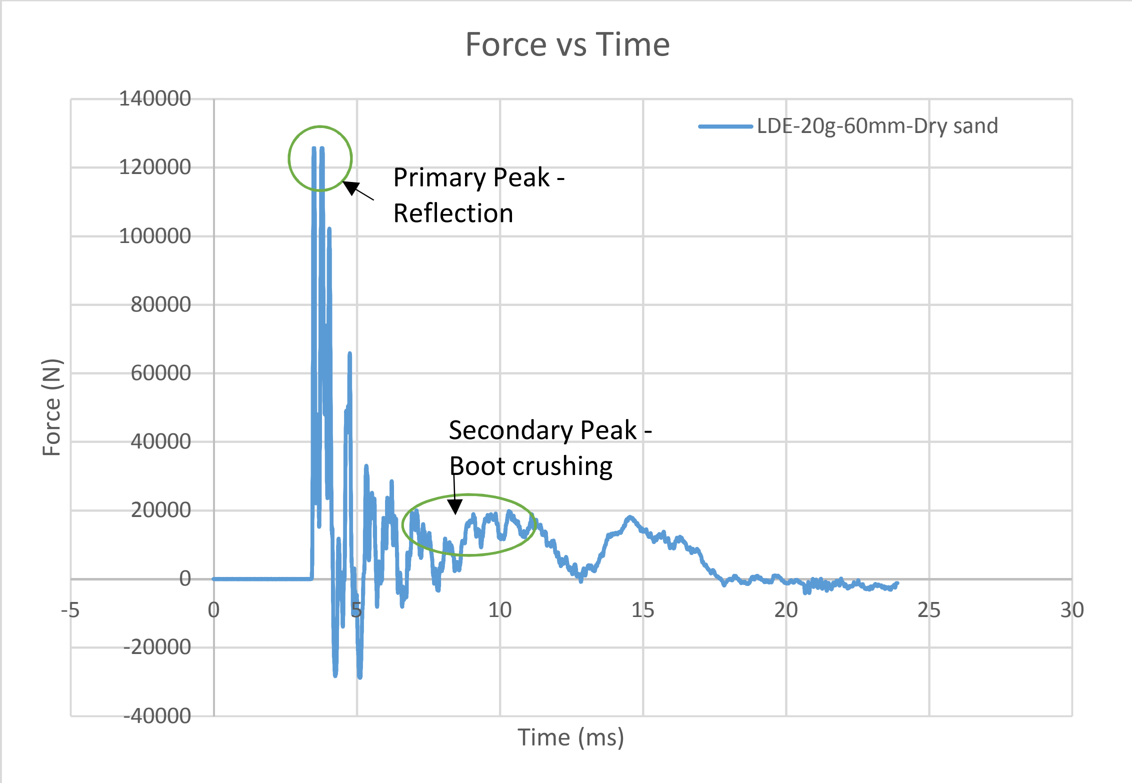


Figure 4.15: Force – time curve for Lowa desert elite boot demonstrating multiple peaks

In either case the experiment demonstrates that a 20g charge generates enough force to exceed the lower limb fracture threshold (8.6kN) by a factor of greater than ten, if the peak force of the first event is considered, and by a factor of two at least if the second event is considered. The displacement, boot velocity and the sand velocity are calculated using the high – speed video. Unfortunately, it was not possible to record the load data for the British combat boot when wet sand (5%) was used due to a failure in the load cell. From the high speed video, it is instantly noticeable that the surrogate limb undergoes only a small amount of displacement (mean = 15.2mm s.d. = 4.0mm) as can be observed from the data above (table 4.3). This is due to the limb being preloaded with a fixed weight (30kg) to simulate half a weight of an average human being. The boot velocity calculated from the high speed video is not actually the boot velocity but rather the velocity at which the weights at the top of the rig move since the boots are quickly covered by sand the moment the experiment is initiated which makes its estimation difficult if not impossible.

Although the experimental trial doesn't have enough data to conduct a statistical analysis; initial observations do confirm the previous work done in the literature. Table 4.3 supports the previous work done by Hlady (2004) that increasing the moisture content increases the peak loads measured. Although this cannot be observed in the case of the first peak force it is easily noticeable for the secondary peaks which are the event of primary interest.

After each of the test runs, photos of the boots were taken and damage was categorised based on the physical damage to the boot and if there were any tears on the surface and consequently any ingress of debris. This was done using the boot damage criteria established by Bass et al. (2004). Out of the three boots tested the Lowa desert elite seems to be the most promising. Compared to the Altberg MKII and the British combat boot it was the only one that was able to survive the blast when dry sand was used without any obvious damage other than some minor surface scarring. However, an important point to be observed is that even in the case that the Lowa desert elite's survived with minimal surface damage, the loads measured were several times the lower limb fracture threshold. This confirms the observations made in the literature that the degree of boot damage should not be used as a preliminary indicator of the degree of lower limb injury. Examination of the boots gives a basic understanding of why the Lowa desert elite survived the blast event much better than the Altberg MKII or the British combat boot. The construction of the boot appears superior in the case of the Lowa desert elite's with the uppers cemented into the sole and with the sole having a large sealed lip that covers all the seams of the boot, hence not providing the blast any easy path during the explosive event. This is not the case in either of the other two boots with the sole and the upper appearing to be two separate piece that are moulded together with exposed seams providing weaker points of entry to the blast.

Figure 4.16: Lowa desert elite boots post trial – dry sand

Figure 4.17: Altberg Warrior MKII boots post trial – dry sand

Figure 4.18: British combat boots post trial – dry sand

However, this is not the case when moving over to wet sand; none of the boots were able to survive the blast when the moisture content of the sand was raised to 5%. All of the boots suffered catastrophic failure which huge amount of ingress of environmental debris.

Figure 4.19: Altberg Warrior MKII boot after blast test with 5% moisture sand

Figure 4.20: British combat boot after blast test with 5% moisture sand

Figure 4.21: Lowa desert elite boot after blast test with 5% moisture sand

All of this demonstrates that other than using specialised boots that were designed for this particular purpose it is not possible to get rid of the loads coming into the foot. Hence, this asks the question, instead of trying to minimize the loads into the foot, would it possible to look at this from the point of view of surgical outcome. Since, previously in the literature it has been established, that the biggest risk from a land mine explosion is the debris and gases that enter in between the muscle planes and causes stripping of muscles from the bone, would it be possible to minimize this ingress.

4.3 Part B – Blast tests using gelatine limb as surrogate

Part B describes the preliminary blast experiments using a gelatine limb as a surrogate to compare the performance with respect to a metal surrogate. The reason was two – fold: i) to see the differences in loads transmitted when moving from a metal surrogate that transmits loads quite well to a gelatine surrogate that shouldn't be able to theoretically transmit loads to the same degree, ii) to start developing an understanding of the tissue damage that can occur during a blast event which can only be observed by using a tissue simulant in the form of a gelatine surrogate. This compliments part A of the experimental trials well where it was observed that even a small charge was capable of producing loads well in excess of the lower limb fracture threshold.

As seen from the previous experimental trials; blast tests are very time intensive and it has always been quite difficult to produce reproducible results, in addition to being expensive which makes it difficult to produce a large number of repeats to conduct a statistical analysis. Hence, the purpose of this experiment was not to produce a large number of repeats to conduct a statistical analysis but to get a basic understanding of the tissue damage that can be observed during a blast event.

Baseline data for the blast tests were recorded in the form of load and velocity data. To quantitatively measure the damage sustained to a gelatine limb various options were explored such as the energy transferred to leg by calculating the number of fissures in the leg. However, this was discarded since large portions of the leg are often thrown by the blast and can go missing making an accurate estimation of energy transfer impossible. Hence, the only other option left was to measure how far up the leg the environmental debris travelled.

4.3.1 Materials and methods

4.3.1.1 Test rig

The rig used in part A and the method in which it was set up remained the same for the gelatine surrogate limb blast tests presented in part B.

4.3.1.2 Surrogate

To simulate the lower limb a 20% gelatine limb was used as the surrogate with the following dimensions. Although not as complex as a Frangible surrogate leg or a Canadian lower leg, this type of limb provides a basic physical structure and tissue simulant to be used as a surrogate limb at a fraction of the cost.

Gelatine with Bloom strength 225 – 265 (type 3 ballistic photographic grade gelatine) was used to manufacture all 20% gelatine surrogate limbs (Appendix A). The knee length Wellington boots (figure 4.22) were used as moulds in which the gelatine limbs were made was a size 9 UK. After the gelatine limbs were cured they were removed from the encasing Wellington boots (figure 4.23) by cutting along the vertical seams at the front and back of the boot and the horizontal seams at the sole making sure not to cut into the gelatine. Each of the surrogate gelatine legs weighed approximately 4.5kg.

The limbs were attached to the rig at a metal plate (figure 4.24) which was connected to the pipe that was cast into the legs during preparation. The load cell was just above the metal plate to ensure that there was a good transfer of the load.

Figure 4.22: Dunlop[1] Wellington boots used as moulds for gelatine legs

Figure 4.23: Gelatine leg cut out of the mould along the Wellington boot seams

[1] Dunlop Sport, Derbyshire, United Kingdom.

Figure 4.24: Pipe cast into the gelatine leg used to attach to the blast rig

4.3.1.3 Boots

Following the work done in part A and based on the results it was decided that there was not any reason to test three different boot types using a gelatine limb due to the time constraints involved. Since the Lowa desert elite (size 11 UK) performed the best during P=part A it was decided to continue using it. In addition, the Dunlop Wellington boots into which the gelatine limb was cast was used as a baseline. In the cases where the Dunlop Wellington boots (size 9 UK) (figure 4.25) were used the gelatine limb was not cut out of the boot and inserted into another Wellington but was rather used as is. For the tests with the Lowa desert elite (figure 4.26) the gelatine legs were inserted into the boots and the laces were fastened up to ensure a tight fit followed by which it was attached to the rig.

Figure 4.25: Gelatine limb in Dunlop Wellington boots attached to the blast rig

Figure 4.26: Gelatine limb Lowa desert elite boots attached to the blast rig

4.3.1.4 Sand

The sand used in part A and the method in which it was prepared remained the same for the tests presented in part B. For the following set of trials only sand with ~0% moisture content was used.

4.3.1.5 Test method

The boot was placed on the end of the leg and secured. The load cell (Kistler 9051A) was attached and connected to the computer. Trugs containing sand filled to the brim were placed beneath the rig. The centre of the heel was estimated by lowering the boots such that it was flush with the sand. A plastic tube was pushed into the sand such that it surrounds the centre of the heel perfectly and was buried till its brim. The sand was then excavated from the inside of the tube to enable easier placement of the charge. When satisfied that no more adjustments had to be carried out; either a 20g charge or 35g charge of PE4 was placed at a depth of 60mm after which it was carefully re – covered with sand. A 30kg mass was added to the top of the rig in the form of static weights and the leg carefully lowered until the boot was resting just above the sand, placing no load on the sand. In total the free moving rig shaft (weight 15kg) with the 30kg weights attached at the top and the gelatine surrogate at the bottom weighed approximately 51kg. After the blast, the trug if in one piece was lifted out of the steel cylinder, if not it has to be shovelled out.

The blast events were recorded using a Phantom high – speed video camera (V12) (29000 fps, 5µs exposure time and 256 x 600 resolution). The loads were measured using a Kistler 9051A load cell (range 0 – 120kN) and ImpacqtV3 software.

Having noted and saved copies of the computer data, the boot was replaced on the leg and the procedure repeated. The procedure was later repeated using sand with a 5% moisture content to see if these changes produced results that were observed in literature.

4.3.1.6 Blast test analysis for gelatine surrogate

At the site post – blast, the degree of boot damage was catalogued, photographs of the boot remains was taken and collected and the video stopped and checked. The computer data was checked to determine load while the acceleration is determined post trials from the high speed video. The degree of damage was categorised using the criteria set up by Bass (Bass et al, 2004).

4.3.1.7 Boot damage analysis

Each of the boots was physically examined post blast to determine the degree of damage sustained. These were then categorised according to the boot damage criteria that was developed by Bass et al. (2004). If the tissue simulants (gelatine limb) survived the blast trials, they were first removed out of either the Dunlop Wellington boots or the Lowa desert Elite's. They were then dissected by cutting horizontally along the wound tract assuming the leg was lying on the table on its sides. Debris present in the cavities was photographed and the length of the wound tract was noted.

4.3.1.8 Load and impulse measurements

All of the blast tests were conducted using a Kistler 9051A load washer connected to a Kistler type 5017B multichannel charge amplifier with the data being recorded in ImpacqtV3 software. The force with respect to time was recorded in software which gave the peak force measured. This data was then exported to an excel spread sheet to carry out further calculations and analysis. The total impulse was calculated from the force data.

Table 4.4: Test variables for blast tests using gelatine legs

Burial depth (mm)	60
Charge weight (g)	20, 35
Target	Gelatine surrogate in Lowa desert elite (LDE); Gelatine surrogate in Dunlop Wellington boot (DWB)
Sand	Dry
Load cell	9051A load washer via type 5017B charge amplifier connected to IMATEK c3008 data acquisition system

4.3.2 Results and Discussion

Table 4.5 displays the result of a 20g and 35g charge of PE4 at 60mm depth against gelatine limbs protected by two different boots: Lowa Desert Elite (LDE) and Dunlop Wellington Boots (DWB).

Table 4.5: Results of blast test at 60mm depth using gelatine legs

Firing	Charge (g)	Boot used	Peak force (kN)	Total impulse (N.s)	Displacement (mm)	Peak boot velocity (m/s)	Peak sand velocity (m/s)
1	35	DWB	4.2	8.8	–	–	–
2	35	DWB	64.0	442.5	–	–	–
3	35	DWB	63.7	215.4	29.6	1.1	67.8
4	35	DWB	47.3	194.8	7.5	0.5	43.9
5	35	DWB	64.9	333.3	12.3	0.8	77.6
6	35	DWB	43.5	232.3	–	–	–
7	35	LDE	38.0	191.5	18.0	0.8	70.2
8	35	LDE	25.6	235.7	7.8	0.5	66.1
9	20	LDE	26.9	157.2	8.0	0.5	51.8
10	20	LDE	44.0	383.3	–	–	–

The trials where no displacement, boot velocity or sand velocity recorded was due to a failure in the high speed video triggering. There were only nine trials conducted since on the last trial the load cell was irreparably damaged making further test impossible. The low peak force measured in the first trial was due to a failure in the charge detonating completely. The force vs time data of the trials conducted demonstrates that in certain cases there are two separate events occurring represented by two obvious force peaks. It appears that the first peak is the transmission of the shock wave to the load cell which is a very quick event and the secondary peak is actually the event where the boot gets crushed and the loads are being transferred which is a much slower event. The following are examples of two such trials where one was i) two events one quick and one longer (figure 4.27) and ii) two events that overlap each other (figure 4.28).

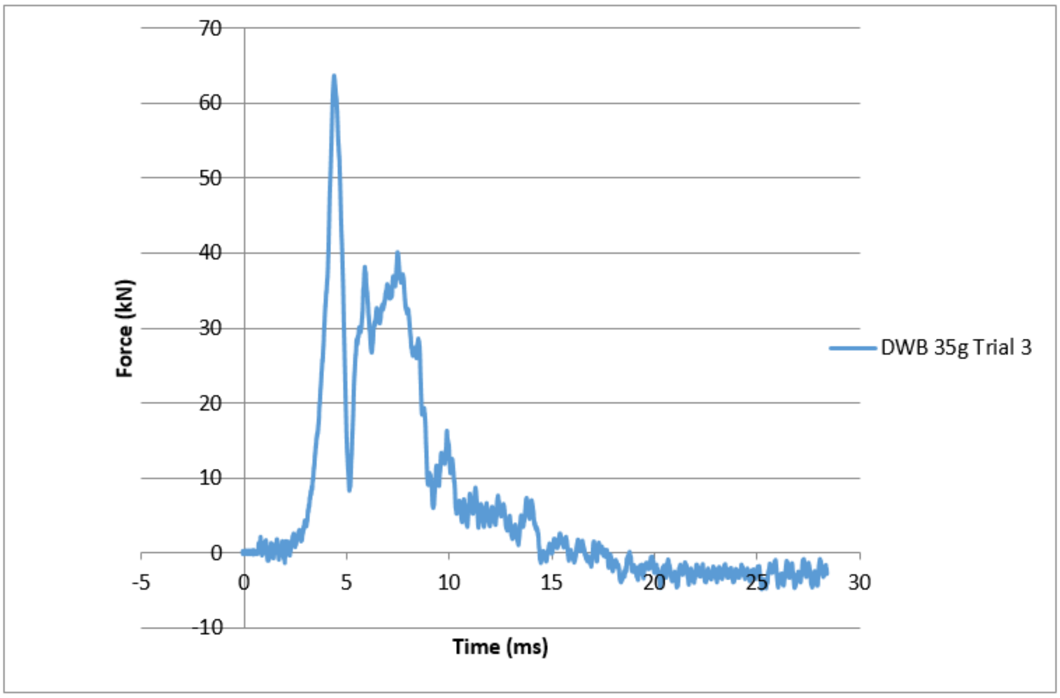


Figure 4.27: Force – time curve showing two distinct peaks for blast test using gelatine legs

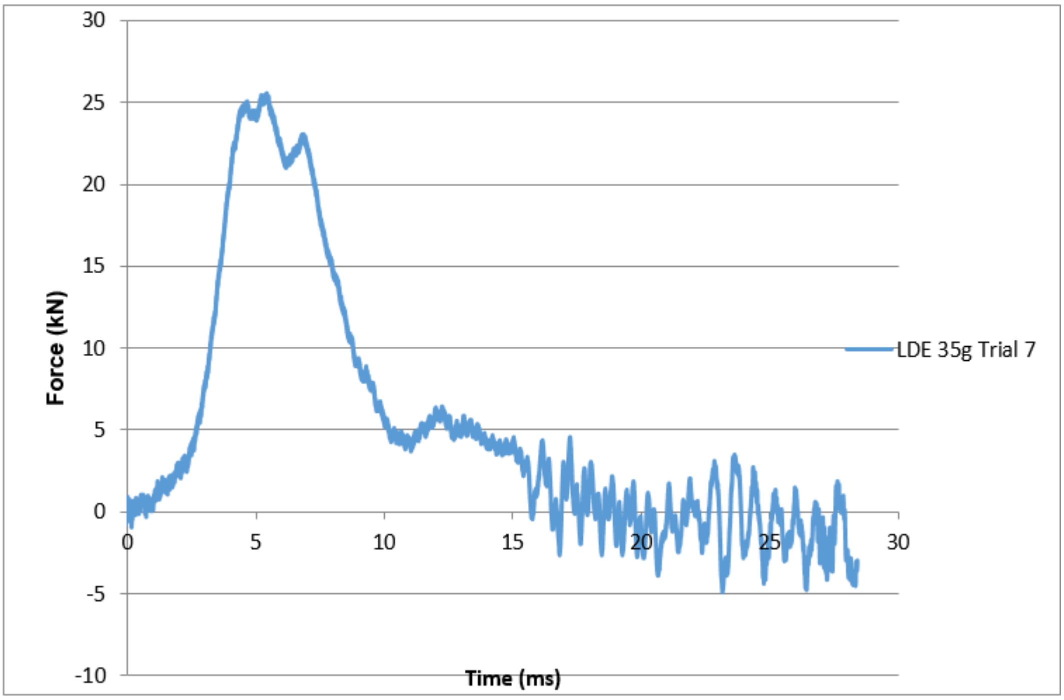


Figure 4.28: Force – time curve showing two peaks that overlap for blast test using gelatine leg

The literature doesn't specify which of the two are of significance. In either case the experiment demonstrates that both a 20g and 35g charge generate enough force to exceed the lower limb fracture threshold (8.6kN) by a factor of at least three. The reason for moving down from a 35g charge to a 20g charge was that at 35g charge while the Dunlop Wellington boots were able to survive quite well; when the Lowa desert elite was tested with the same charge weight it resulted in the boot being completely torn apart which was in contrast to part A of the testing.

From the high – speed video it is instantly noticeable that the surrogate limb undergoes a minimum amount of displacement as can be observed from the data above due to the limb being preloaded with a fixed weight (30kg) to simulate half a weight of an average human being. The behaviour of the sand was the same as in the trials using metal surrogates; hence the boot velocity calculated from the high speed video is the velocity at which the weights at the top of the rig move.

After each of the test run, photos of the boots were taken and damage was categorised as shown in table 4.6 based on the physical damage to the boot and if there were any tears on the surface and consequently any ingress of debris. This was done using the boot damage criteria established by Bass et al. (2004). Out of the two boots tested the Dunlop Wellington boots (figure 4.31) seems to be the most promising. At 35g it managed to stay relatively intact compared to the Lowa desert elite's (figure 4.32).

Table 4.6: Results of blast test on gelatine leg with respect to depth of penetration and boot damage criteria

Firing	Charge (g)	Boot used	Damage description	Depth of penetration (mm)	Boot damage level
1	35	DWB	No damage due to partial detonation	0.0	BD1
2	35	DWB	Sole cracked	136.4	BD3
3	35	DWB	Sole intact, sides and seams ripped open	149.5	BD3
4	35	DWB	Sole intact, minor tear on the side	72.0	BD2
5	35	DWB	Sole, sides and seams ripped open	195.8	BD3
6	35	DWB	Sole, sides and seams ripped open	100.5	BD3
7	35	LDE	Boot in pieces, gelatine leg destroyed	–	BD3
8	35	LDE	Boot in pieces, gelatine leg destroyed	–	BD3
9	20	LDE	No sole damage, major tears in sides from sole to the top	31.5	BD3
10	20	LDE	Minor surface damage to sides and sole with minimal tearing	0.0	BD2

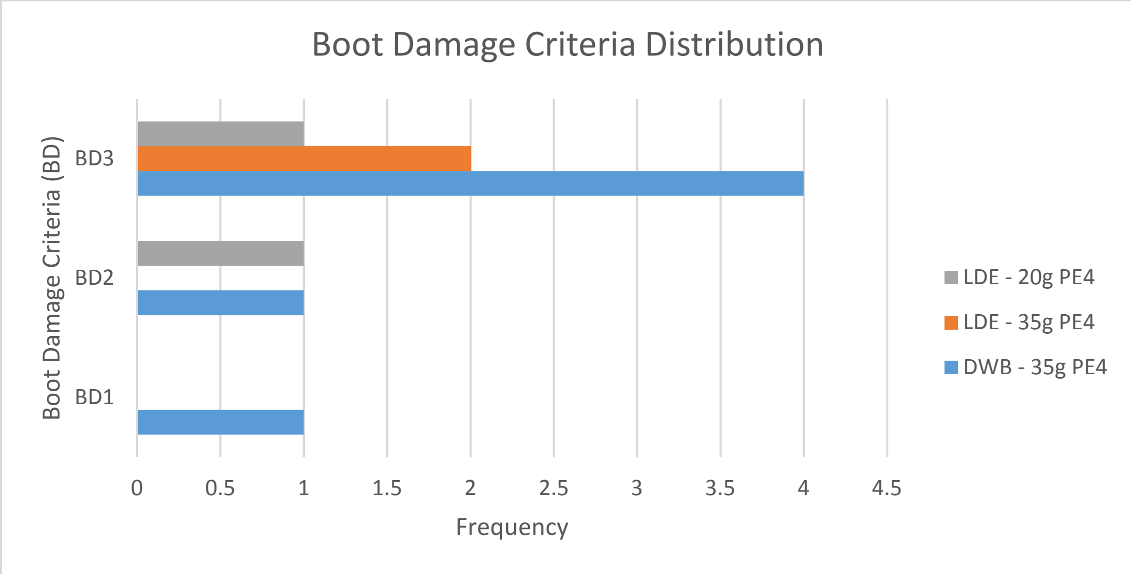


Figure 4.29: Frequency distribution of the boot damage criteria for gelatine legs using different boots and charge weight for blast tests

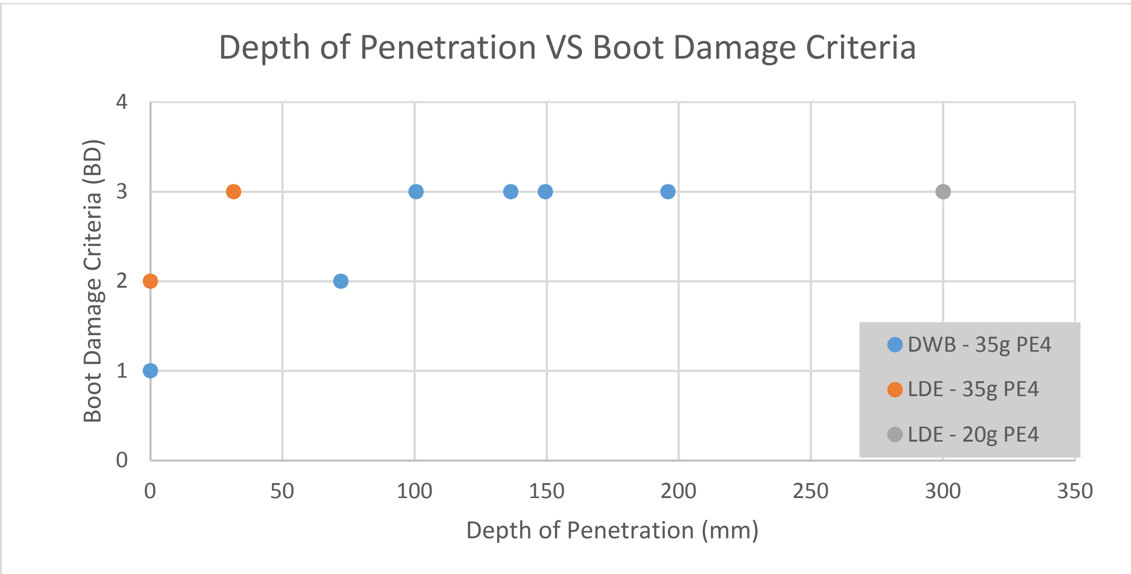


Figure 4.30: A graph of depth of penetration against boot damage criteria for gelatine legs using different boots and charge weight for blast tests

Figure 4.31: Dunlop Wellington boot post trial 2

Figure 4.32: Lowa desert elite's post trial 7 and 8

4.4 Discussion of results from Part A and Part B

All the previous work in the literature (Lans,1999; Fujinaka et al, 1966; Harris et al, 2000; Bergeron et al, 2006; Bergeron et al, 2007; Van der Horst et al, 2008; Mah et al, 2007; Nicol, 2011) has been focused on tying to minimise the loads transferred to leg either by developing new types of boots or by incorporating mechanisms into it to achieve the desired result. The purpose of the current trials was to get an understanding of the loads produced by a small charge and whether these could be mitigated by using commercially available footwear. However, as demonstrated in part A and part B, the loads produced by even a 20g charge are larger than the lower limb fracture threshold by factor of three at minimum. As mentioned previously there are two peaks that can be observed in the graphs (figure 4.27), the primary peak is a very quick event which is the transfer of the shock wave to the load cell and the secondary peak is a slower event where loads are transferred as the boot gets crushed. For the purpose of this study the primary was considered as the important one as it signifies the peak loads that would be measured during a blast event.

When comparing the loads from part A with metal surrogate to part B with the gelatine surrogate, it is immediately observable that the peak loads measured are much lower in the case of the gelatine surrogate. This would make sense as gelatine would be less efficient at transferring loads than metal. This is because the metal surrogate is a lot stiffer having a higher Young's modulus (200 x 10^6kPa) (Wolfenden, 1990) compared to gelatine (80 – 120kPa) (Karimi et al, 2014). This means that gelatine surrogate has a higher compliance than the metal surrogate, and hence loads are not easily transferred axially resulting in bulging of the gelatine surrogates during the blast (figure 4.33). This poses an immediate problem when comparing the data with the literature, since all of the work done previously has been done either using a metal limb or a hybrid limb such as a frangible surrogate legs or the Canadian lower legs. From a technical point of view, the hybrid limb would be the optimum surrogate to use in this type of testing since it offers the best of both worlds; the mechanical movement of a human limb and a tissue simulant for studying wounding. However, since the testing being conducted is highly destructive combined with the cost of each of the hybrid limb, it makes its use unfeasible where each limb could only be used once.

Figure 4.33: Bulging of gelatine surrogates during blast test

It can also be observed that the performance of the boot changes depending on the type of surrogate used. In part A of the trials using a metal surrogate the Lowa desert elite's performed better when compared to the other boots. This can be attributed to details of its construction such as covered seams and a harder sole. The same cannot be said when using a gelatine surrogate; here the Lowa desert elite's suffered catastrophic failure at 35g when compared to the Dunlop Wellington boots. This would not generally be expected keeping in mind the purpose of both of these products; the Lowa desert elite's being designed for much harsher use. The reason for this can be explained on the basis of the materials used; the Dunlop Wellington boots is made of materials that have considerable flexibility when compared with the Lowa desert elite's; hence when the blast occurs the Dunlop Wellington boots warp along with the gelatine and are able to survive the blast with a few tears along weak points (figure 4.33). The survivability of Dunlop Wellington boots can be explained since Dunlop Wellington boots have a lower Young's modulus (1000kPa) compared to Lowa desert elite's (100 x 10^3kPa) (Wolfenden, 1990). Hence, the Dunlop Wellington boots are able to balloon to accommodate for the bulging of the gelatine surrogate. The same cannot be said for the Lowa desert elite's and the boot suffers catastrophic failure with the gelatine limb being destroyed into multiple chunks. This was not the case when moving to a lower charge weight (20g PE4) when the Lowa desert elites performs better.

There are a number of problems associated with conducting such trials on an explosive range. The major ones being time constraint and cost. On average a single firing takes about an hour, due to the time required to setup, make sure the debris from the previous trial has been cleared and making sure the equipment is working which restricts the number of repeats that can be done. Due to the amount of equipment required to capture the required data, if one of them fails to capture, it is not possible to go back and repeat the trial.

In addition, there are a large number of variable involved in a test of this magnitude such as the charge used, partial or complete detonation, burial depth, moisture content, equipment used, temperature of the gelatine limbs; each of these must be tightly controlled every time to get consistent results. Hence, even a small change in any of the depending variables, such as the moisture content of the sand will produce varying results, as can be seen from the initial testing.

Since it was demonstrated in part A and B of this PhD that the loads measured exceed the lower limb threshold even against a small charge when using a metal or gelatine surrogate, reducing the load might not be the answer and an alternate solution was required. The literature identifies that the degree of contamination suffered as a result contributes to the surgical outcome of the leg. Hence, it might be possible to offer better protection to the lower limb not by minimizing the loads transferred but by minimizing the degree of ingress of environmental debris which in turn would minimize the amount of tissue excised after a land mine explosion. This can be achieved if the protection is designed with surgical outcomes in mind.

Chapter 5 of this PhD will deal with developing a gun based test that will be able to replicate the effects of a blast test while overcoming its limitations e.g. cost, time constraint and repeatability.

Chapter 5: DEVELOPMENT OF A NEW TEST METHODOLOGY TO SIMULATE BLAST TESTS

5.1 Introduction

As discussed in chapter 4, blast trials involve a large number of variables, which makes producing reproducible and repeatable results very difficult. This lines up with what can be observed in the literature, where it was difficult to compare the results of the blast test to one another due to the differences in the variables being considered. In addition, the cost and the time associated with each of the trials necessitate the development of a new test method that is able to address all of the above issues. Hence, for a test method to be able to replace blast testing it needs to minimize the variables involved and requires the development of a standardised test that is able to consistently produce reproducible and repeatable loads and damage that are comparable with those obtained from blast testing while being relatively quick to conduct and cheaper.

Developing a gun based test method to replace blast testing requires it to be validated, which means that the performance of the blast test be quantified. When a target is in contact with the soil during blast test it undergoes a change in momentum which is defined by the impulse value. Hence, total impulse can be used as one parameter to quantify the performance of the blast test. The other parameter is the energy of the sand that is impacting the target, since this is what primarily causes the change in momentum of the target. Hence, the initial part of this chapter will deal with quantifying the performance of the blast test in terms of total impulse and energy of the sand impacting the target.

Chapter 5 discusses the work that was undertaken in order to arrive at the final version of the gun based test setup going through the different iterations and discussing how different variables were changed to match the values mentioned previously. This chapter is split into Six parts: Part A – Quantifying the performance of blast tests, Part B – Preliminary gun based testing, Part C – Testing 160mm and 180mm sabots, Part D – Testing 160mm sabots at different distances and propellant weights using a metal surrogate or a boot, Part E – Determining the cause of penetration when using 160mm paper sabots and Part F – A replacement for paper sabots.

5.2 Part A – Quantifying the performance of blast tests

Fujinaka et al. (1966) stated that it is not the loads but rather the total impulse and the impulse per unit area that need to be used when evaluating the performance of boots. Where the total impulse, as discussed in chapter 2, is defined as the integral of a force over the time interval for which it acts, which is the area under a force time curve (Serway, R.A. and Jewett, J.W., 2013). Hence, it is necessary to quantify blast tests in terms of total impulse and impulse per unit area. Since there are no good analytical methods to determine the total impulse three different methods will be used to estimate it.

Equation (1) provided by Tremblay (1998) as discussed in chapter 2 allows for the total impulse to be calculated. While this equation allows for the total impulse to be estimated it has to be kept in mind that it is validated for a limited burial depth and has not been validated for a zero standoff distance.

Total impulse, $I = \left(\frac{0.5857}{\varsigma^2}\right)\left(1 + \frac{7D}{9Z}\right)\sqrt{\frac{\mathrm{PE}}{\mathrm{Z}}}$ … equation (1)

For the blast tests using 20g of PE4 at a burial depth of 60mm (0.06m), the following calculations can be made. The dimensions for a 20g mine are as follows;

Radius, r = 0.023m

Height, h = 0.012m

Hence, the following calculations can be made;

D = burial depth + half the height of the mine

= 0.06 + 0.006

= 0.066m

Since the target is sitting flush with the soil,

Z = 0.066m

P = 1600 kg/m^3 (density of sand) (Fiserova, 2006)

E = energy per kg x weight of charge

= 5.621 x 0.020MJ (Rigby et al, 2015)

$= 0.112 \times 10^{6}$J

A $= (\pi r^{2})$

$= 0.00167$m^{2}

Then by putting the data into the equation (2) from chapter 2;

$$Ϛ = \frac{D}{\left(Z^{\frac{5}{4}}\right)\left(A^{\frac{3}{8}}\right)\left(\tanh\left(\frac{2.2D}{Z}\right)^{\frac{3}{2}}\right)}$$

$Ϛ = 22.068\text{m}^{-1}$

Substituting these values into equation (1):

I = 111.7N.s

This value for total impulse will be the same for blast tests both using dry and wet sand. This is because the equation cannot account for changes in moisture content and is not validated for it.

Another way for calculating the total impulse is from the velocity of the sand cloud. The velocity of the sand cloud has been estimated from the high speed video (table 5.1).

Table 5.1: Velocity of sand cloud for blast test

Firing	Boot used	Soil condition	Sand velocity (m/s)
1	ALT	Dry	65.5
2	ALT	Wet	62.1
3	BCB	Dry	70.4
4	BCB	Wet	53.6
4	LDE	Dry	59.5
5	LDE	Wet	53.5

For the trials with dry sand the velocity was calculated and it results in an average velocity of 65.1 m/s. Since in the blast test the entire mass of the sand doesn't impact with the boot, an assumption can be made that the sand above the mine is in the form of a cylinder that is 60mm high and has the same radius as that of the surrogate limb. Then the volume of the impacting sand can be calculated as follows:

Radius of the sand column, r = 0.1m

Height of the sand column, h = 0.06m

The volume of the sand column = $\pi(r^2)h$ = 0.002m^2

The density of sand is known to be 1600kg/m^3, hence the mass of the sand can be estimated:

Mass = Density x Volume = 0.0019 x 1600 = 3.0kg

Since the initial velocity of the sand at the start of the blast trial was zero and the final velocity and the mass of the sand are known. The total impulse can be calculated using the following equation.

Total impulse, I = m ($v_2 - v_1$); … equation (3)

Where,

m = mass of the sand

v_2 = final velocity of the sand

v_1 = initial velocity of the sand

Hence, I = 3.016 x 65.11 = 196.4N.s

Similarly, total impulse can be calculated for the wet sand using equation (3). It results in a total impulse value of 170.1N.s.

From the calculation of the total impulse using two methods it can be seen that total impulse value calculated by Tremblay equation was lower than the total impulse calculated from the velocities.

It has to be kept in mind that this total impulse was calculated assuming there was a fixed column of sand above the mine, and hence the value would be quite different if the weight of the sand was known correctly. Additionally, this is the upper limit of the total impulse, since the formula assumes that there is not any loss in the weight of the sand during the event, which is not true since the sand doesn't behave as a solid but flows around the target.

For the blast tests the total impulse was also calculated using the force – time curve (table 5.2), this was because during the blast the sand tended to obscure the high speed video making measurements of velocity of the sand cloud inaccurate with different velocities for dry (mean = 65.1m/s, s.d. = 5.5m/s) and wet sand (mean = 56.4m/s, s.d. = 4.9m/s). In addition, logistically it was not possible to weigh the sand overburden while conducting the tests to determine the total impulse imparted to the boots. This makes both of the previous estimates inaccurate but provides a good indication of what is needed. This shows that the total impulse calculated from the force time curve falls in between both the lower value of the total impulse (111.7N.s) from the Tremblay equation and the higher value (196.4N.s) calculated from the sand velocity for almost all of the cases. All of this shows that it is difficult to quantify a blast and the values calculated depends on the method used.

Table 5.2: Total impulse for blast test calculated from the force – time curve and sand velocity compared to 111.7N.s total impulse from Tremblay (1998) equation

Firing	Boot used	Soil condition	Total impulse from force – time curve (N.s)	Total impulse from sand velocity (N.s)
1	ALT	Dry	133.8	197.6
2	ALT	Wet	184.6	187.2
3	BCB	Dry	145.9	212.3
4	BCB	Wet	–	161.5
4	LDE	Dry	175.5	179.3
5	LDE	Wet	212.1	161.3

As shown in chapter 4, previous research by Fujinaka et al. (1966) has shown that the two important criteria when evaluating blast resistance is the total impulse and the impulse per unit area. All the boots used in the blast test differed in their construction and underwent critical failure outputting different loads and total impulse. Hence, in order for gun based tests to be developed as a replacement for the blast test they need to match or exceed the blast test total impulse or impulse per unit area. Since from the previous calculations, the impulse for the blast tests is known, it is necessary to calculate the impulse per unit area, this is because the area over which the sand cloud acts may vary as different iterations of the gun based tests are conducted.

For the blast test in the case of a Lowa desert elite size 11 boot, the impulse per unit area can be calculated. The area of the sole was calculated using the ImageJ[1] software using the measurement tool to calculate the area. Since the sand cloud acts over the entire sole, the total sole area was used for the calculation.

Area of the sole for the blast test, $A = 0.022m^2$

[1] Image processing program developed by the National Institutes of Health, Maryland, United States.

Hence, impulse per unit area = I/A

For the total impulse value calculated from the Tremblay paper, I/A = 5073.6N.s/m^2

For the total impulse value calculated from the high speed video, I/A = 8925.5N.s/m^2

For the total impulse value calculated from the force – time curve for Lowa desert elite boot, I/A = 7975.7N.s/m^2

These calculations show that since the total impulse value changed depending on which method was used to obtain it, the impulse per unit area value would also change. Out of the three methods the value calculated using the equation provided by Tremblay is the most inaccurate for this particular type of blast testing since it is based on a mine that is offset from the target and is applicable when there is a standoff distance. However, it still provides a good rough estimate and a lower limit which has to be met in future tests. Hence, in order for gun based tests to match the performance of blast tests it needs to match or exceed impulse per unit performance.

From the same values calculated previously, the energy of the sand cloud and the energy per unit area can be calculated for the blast test. For the blast tests the weight of the sand and the velocity of the sand cloud are known from the previous analysis, hence the following calculations can be made;

Total energy release from explosive charge = Energy per kilogram x weight of charge

For 20g PE4, E = energy per kg x weight of charge

= 5.621 x 0.020 = 0.112MJ

Energy of the sand cloud can be calculated as follows;

Weight of sand, m = 3.0kg

Velocity of the sand cloud, v = 65.1m/s

Hence, Energy, E = 0.5mv^2 = 6358.9J = 6.4KJ

This shows that the energy of the sand cloud is lower than the total energy that is possible from the detonation of 20g of PE4. The energy of the sand cloud is lower as expected since there is loss of energy into the sand in order to move it and loss into the air.

Since the area over which the sand cloud acts for the blast tests is known, the energy per unit area can be calculated. Hence, for the blast tests as calculate previously;

Area of the sole over which the sand cloud acts, A = $0.022m^2$

Energy per unit area, E/A = 6.3/0.022 = $289.1KJ/m^2$

Hence, in order for gun based tests to match the performance of blast tests it needs to match or exceed the energy and energy per unit area performance.

5.3 Part B – Preliminary gun based testing

As described previously, blast testing has a number of problems, such as the necessity to conduct all the tests outdoors, the use of buried charges and safety procedures that are introduced in the test since the explosive technician has to place the charge and detonator by hand before burial. This means that range procedure first ensures safety of all involved and accuracy of the test is secondary. A gun based system would enable a more accurate testing process by eliminating several of these limitations since the propellant used will be easier to use and safer to handle. Moreover, a gun based system would provide the ability to accurately place the load while allowing for fine adjustments to be made regarding the aim.

Part A describes the preliminary experiments that were done in order to determine if it was possible to replicate the blast test results using a gun based test. This means being able to produce similar loads to the blast test and being able to produce penetration of the boots being tested. The blast tests involved a contact explosion of a fixed charge weight at a particular depth which is not the case in gun based testing. Hence, the preliminary testing dealt with selection of the sabot to fire the sand, the weight of the sand being fired and distance at which the sand is fired from. The aim was to launch a mass of sand to replicate the loading from blast tests due to a buried charge. This required a measurement system that would allow for the loads to be measured and a gun based system for the sand to be launched from so that it can be in the correct geometry.

The purpose of this trial was to get a general understanding of what could be achieved using a gun based test with respect to the objective in mind. Hence, it was not undertaken to perform a large number of repeats to conduct a thorough statistical analysis. The velocity of the sand was the only measurement that was taken for this part.

5.3.1 Materials and methods

5.3.1.1 Test rig

A gun based system requires two main features, a launcher/loading system, – the gun and a horizontal target mounting system – the target. As part of the preliminary testing a new rig was designed, which was suspended from the ceiling (figure 5.1 and figure 5.2). A 30kg (3 x 10kg plates) weight was placed at the back to simulate half the weight of an average person and the limb was attached at the front. In the case of the gelatine limbs, a small gauge rope was used to provide additional support to the leg to prevent sagging. The entire setup was suspended at two points using a galvanised steel wire rope and secured using a Gripple™[1] (figure 5.3). This allowed for the height and alignment adjustments to be made as needed. The entire rig was allowed to freely swing with the only resistance offered being the weight of the rig combined with the 30kg weight plates which had a total weight of 45kg. The metal surrogate was attached to the front of the rig and was used as the target.

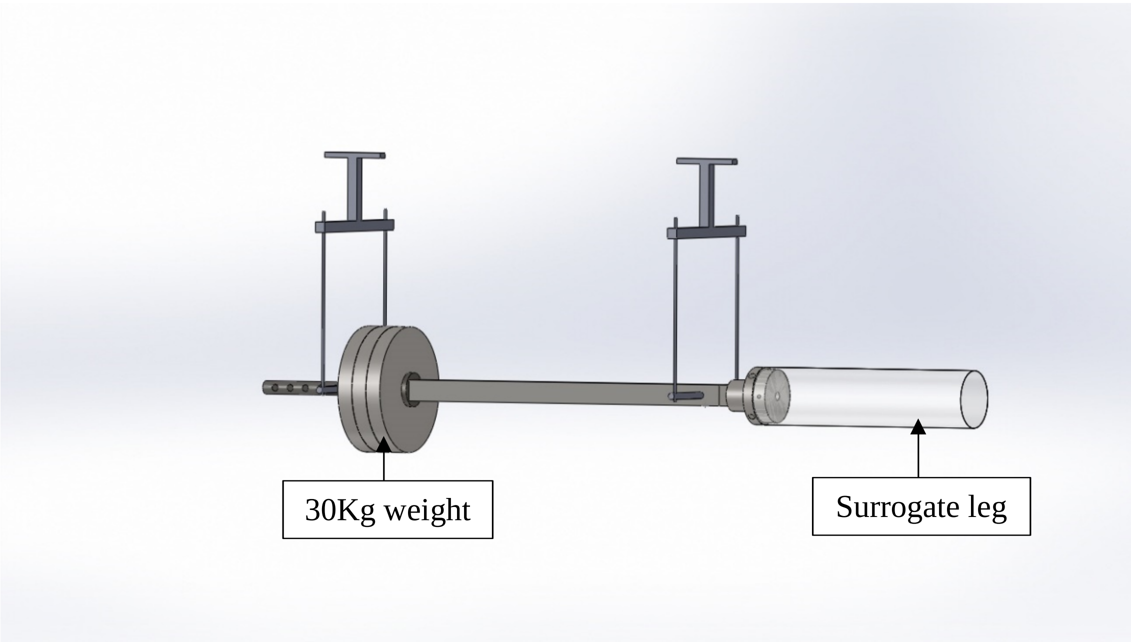


Figure 5.1: Graphical illustration of the test rig used for gun based testing with metal surrogate attached

[1] Gripple UK, Sheffield, United Kingdom.

Figure 5.2: Test rig used for gun based testing with Dunlop Wellington boot mounted onto metal surrogate

Figure 5.3: Gripple used for suspending the test rig from the ceiling for gun based tests

5.3.1.2 Sand

The sand used for the testing was plain playground grade silica sand which was from the same batch that was prepared for the blast tests and was dried in the same way (see section 4.2.1.4). For these trials only sand with ~0% moisture content was used, since the sabot was prepared a day in advance and it would not have been possible to control the moisture content accurately. Moreover, there was a possibility that the wet sand would have been able to change the geometry of the sand coming out of the gun.

5.3.1.3 Sabot

In blast tests, the sand under the boot acts on it at the same time, as a solid mass. To replicate it, the gun based system needs to use a sabot. A sabot is a device that has a smaller diameter than the barrel and ensures that the projectile is in the centre of the barrel when fired. Since the sand doesn't have a defined shape a sabot is required to contain the sand and ensure that all the sand comes out at the same time. In the gun based system paper sabots are used as they should not adversely affect the loads measured. Three different paper types were used to make sabots: i) white inkjet paper (PP) (80g/m^2), ii) brown wrapping paper (BP) (65g/m^2) and iii) paper kitchen towels (TP) (35g/m^2) (figure 5.4). The papers were cut into the required dimensions to get sabots of different lengths. The sabots were made by wrapping around a brass cylinder (150mm long; diameter 29mm) (figure 5.5) and sealing it at the bottom and along the vertical seam using commercial masking tape (figure 5.6). The sabots were then filled with different weights of sand (table 5.3) and the tops were sealed by folding them securely. This was done to allow the sand to easily escape when the sabots were shot from the gun.

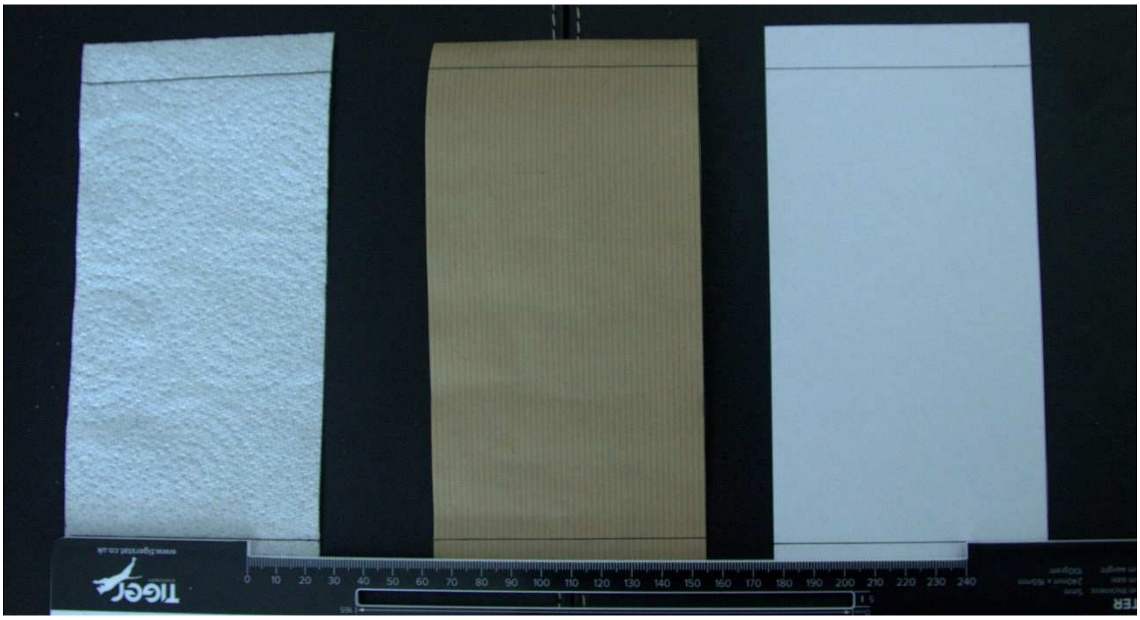


Figure 5.4: Kitchen towel, brown paper and inkjet printer (left to right) cut to size for making 160mm sabots

Figure 5.5: Brass cylinder used for preparing paper sabots

Figure 5 6: Paper sabots prepared after sealing seams using masking tape

Table 5.3: Sabot variable for different lengths and sand weight

Length (mm)	Dimension (L x W) (mm x mm)	Weight of sand (g)
100	130x91	114
120	150x91	135
140	170x91	160
160	190x91	178
180	210x91	205
200	230x91	228

5.3.1.4 Preliminary test setup and method

The sabots were fitted into a Rarden shell (figure 5.7) for firing. 40g of propellant (N160 VihtaVuori smokeless powder, 3.65MJ/kg) (figure 5.8) was used and test conducted to determine the different velocities that could be obtained using different sabot sizes containing different weights of sand. The sabots were fired using a 30mm barrel 1135mm long (figure 5.9). The target for these sets of trials was the surrogate limb without any boot which was connected to the rig using a metal plate and placed 100mm (figure 5.10) from the end of the muzzle.

Figure 5.7: Rarden shell used for firing paper sabots

Figure 5.8: VihtaVuori[1] N160 smokeless powder

[1] Nammo Group, North Yorkshire, United Kingdom.

Figure 5.9: 30mm barrel fitted onto housing used for gun based testing

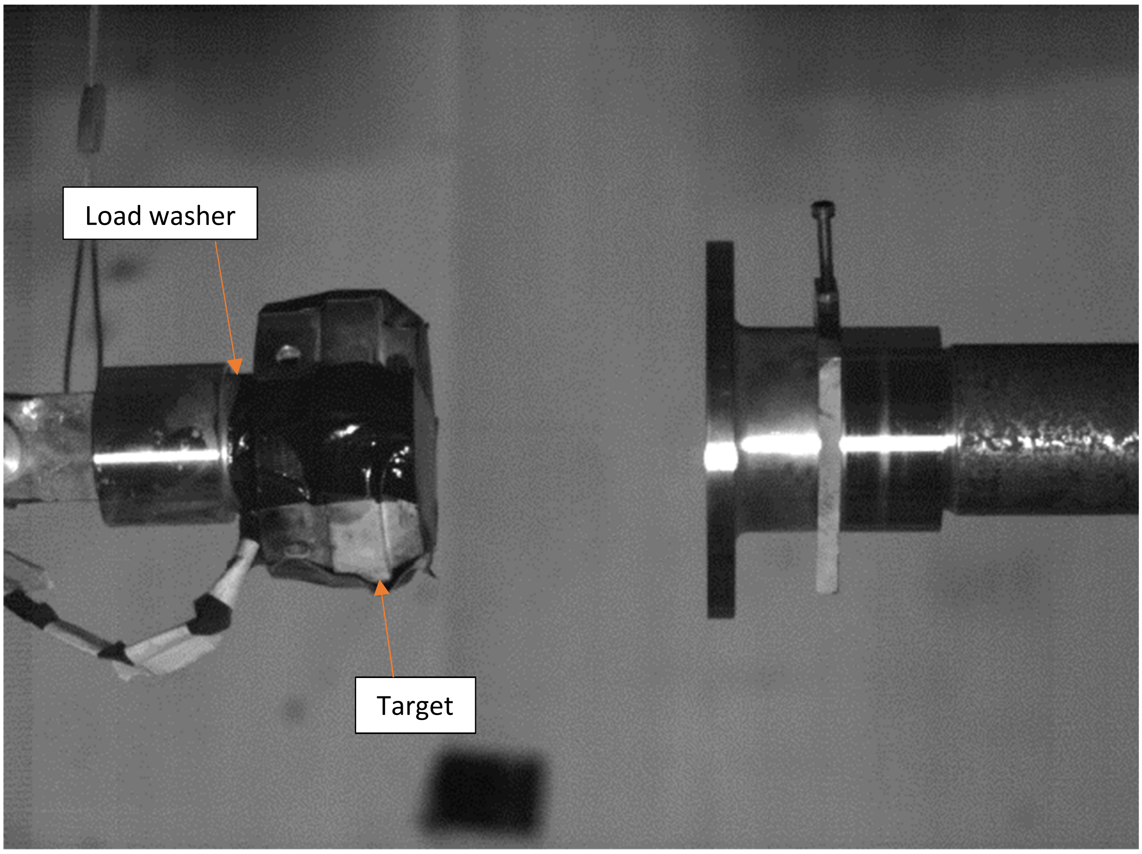


Figure 5.10: Target used for testing different paper sabot lengths

The impact events were recorded using a Phantom high – speed video camera (V12) (10000 fps, 6μs exposure time and 1280 x 480 resolution) from which the velocities were recorded after calibration. The target was illuminated from the side and the back using two 2kW halogen lights. A Kistler 9061A (range 0 – 200kN) (Appendix C) (figure 5.11) load washer was placed in between the metal plate and the rig, which was connected to a PicoScope[1] 3000 series oscilloscope (figure 5.12) with the data being recorder on the PicoScope oscilloscope software (version 6.10.18).

[1] Pico Technology, Cambridgeshire, United Kingdom.

Figure 5.11: Kistler 9061A load washer

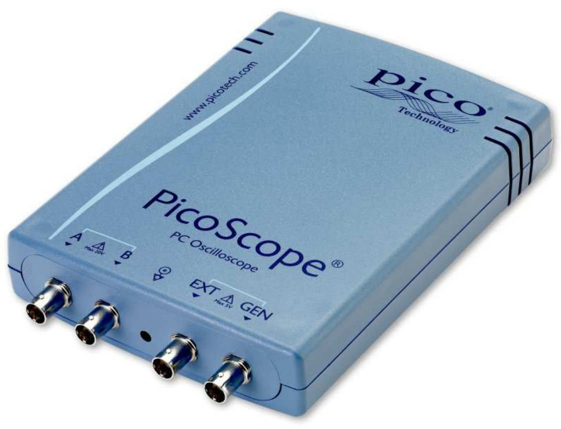


Figure 5.12: PicoScope 3000 series oscilloscope

Table 5.4: Test variables for preliminary gun based test using different sabot types of different length

Distance (mm)	100
Propellant weight (g)	40
Target	No target; Plate
Sand	Dry
Sabot	100 – 200mm sabots; Brown paper (BP); White paper (PP); Kitchen towel paper
Load cell	9051A load washer via PicoScope 3000 connected to PicoScope oscilloscope software

5.3.2 Results and discussion

Table 5.5 displays the impact velocities that were obtained using 40g of propellant from three different paper types, of six different lengths, each containing a measured weight of sand.

Table 5.5: Results of gun based tests using different paper sabots

Sabot length (mm)	Velocity of sand cloud (m/s) Sabot type		
	White paper (PP)	Brown paper	Paper towels
100	Not recorded	341.3	345.5
120	439.4	Not recoded	261.4
140	360.2	350.9	541.7
160	609.1	619.7	613.5
180	439.4	306.8	Not recorded
200	492.5	416.8	Not recorded

After the trials based on the above results it was decided not to continue using the paper towels; the paper towels lacked the structural stability that the other two sabot types provided making it difficult to fit into the shell and consequently the barrel, moreover the velocities produced by them were very inconsistent (mean = 465.5m/s, s.d. = 165.1m/s). The high speed video analysis showed that the geometry of the sand cloud was a lot more consistent for brown and white paper sabots (figure 5.13). The brown and white paper sabots produced sand clouds that were more concentrated with well – defined margins.

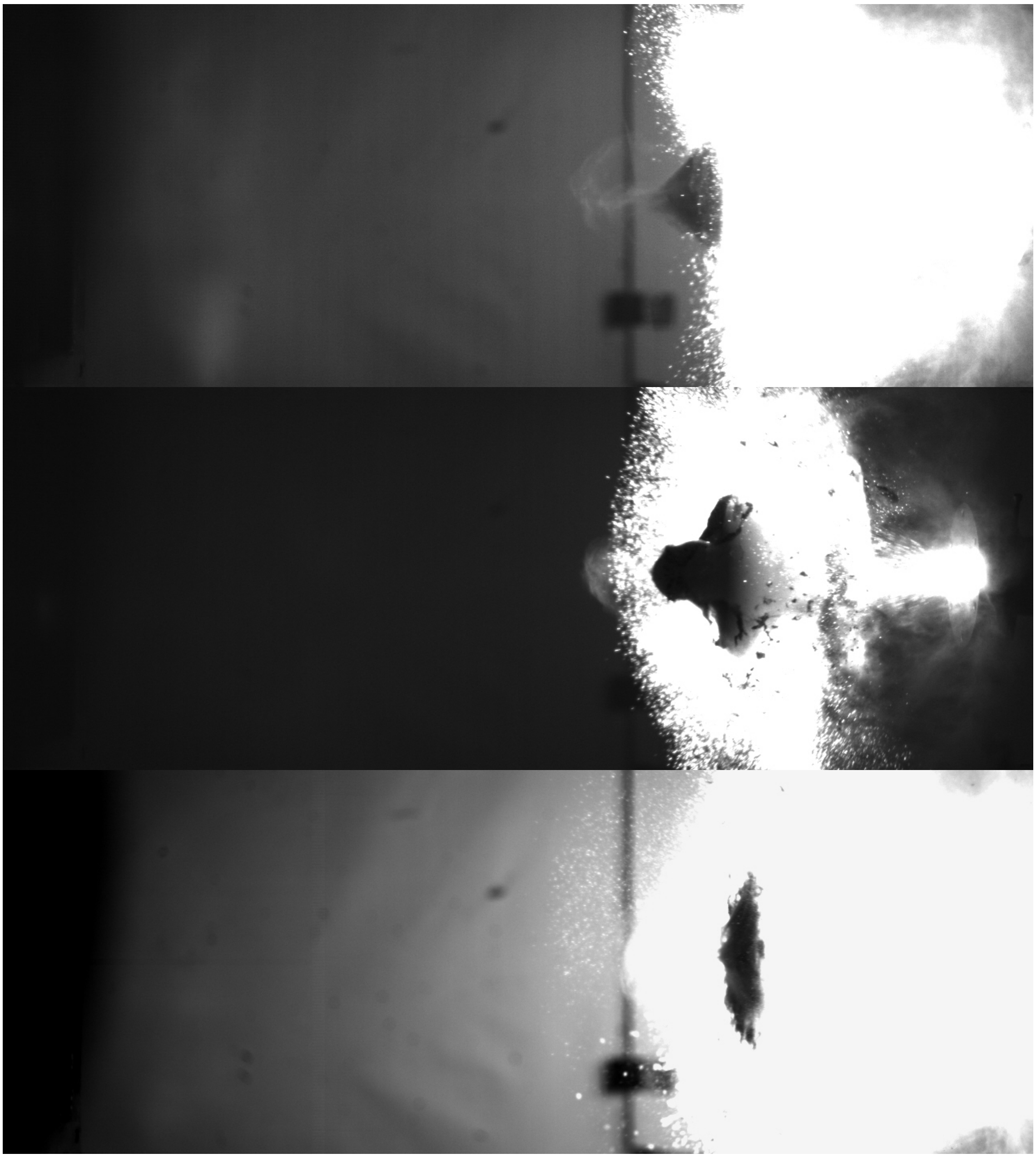


Figure 5.13: Sand cloud geometry from three different 160mm paper sabots, i) brown paper, ii) white paper and iii) paper towels (top to bottom)

The trials were then repeated with a distance of 100mm between the muzzle and metal plate target so that the loads produced could be recorded.

Table 5.6: Total impulse analysis for paper sabot trials

Sabot		White paper (PP)		Brown paper	
Length (mm)	Weight (g)	Velocity (m/s)	Total impulse (N.s)	Velocity (m/s)	Total impulse (N.s)
100	114	Not recorded	N/A	341.3	38.9
120	135	439.4	59.3	Not recoded	N/A
140	160	360.2	57.6	350.9	56.2
160	178	609.1	108.4	619.7	110.3
180	205	439.4	90.1	306.8	62.9
200	228	492.5	112.3	416.8	95.0

For future trials the 100mm, 120mm and 200mm sabots will not be considered, this was because it was felt that the 100mm and 120mm sabots would not produce sufficient impulse for the sand to penetrate the boot and cause tissue injury; while the 200mm sabot had sufficient impulse, it was too long to be comfortably fit into the barrel. Looking at the preliminary data (table 4.3) it was decided to continue using the 160mm sabots because of the higher velocities recorded for both brown and white paper sabots resulting in higher impulse values; when deciding between the 140mm and 180mm sabots it was decided to continue using the 180mm sabots over the 140mm because of the higher impulse values (90.1N.s for white paper 180mm sabots vs 57.6N.s for white paper 140mm sabots). No load data was recorded for these trials as they were meant to narrow down the sabots to be used for future work.

5.4 Part C – Testing 160mm and 180mm sabots

Part C describes the preliminary experiments that were done with 160 and 180mm sand sabots to record the results produced by the gun based test. The purpose of this trial was to narrow down the sabot used and to get a general understanding of the loads that could be produced with reference to the blast test. Hence, it was not undertaken to perform a large number of repeats to conduct a thorough statistical analysis.

For the next trials the 160mm and 180mm white paper (PP) and brown paper (BP) sabots were shot at 100mm distance from a metal plate and the loads and velocities were recorded. The impact load and velocity of the sand were the only measurements that were taken.

5.4.1 Materials and methods

5.4.1.1 Test rig

The test rig used in part B, and the methods by which they were assembled remained the same for the testing in part C.

5.4.1.2 Sand

The sand used in part B, and the methods by which they were produced remained the same for the testing in part C.

5.4.1.3 Sabot

Two different paper types were used to make sabots: i) white inkjet paper (PP) ($80g/m^2$) and ii) brown wrapping paper (BP) ($65g/m^2$). The papers were cut into the required dimensions to get sabots of different lengths. The sabots were made by wrapping around a brass cylinder and sealing it at the bottom and along the vertical seam using commercial masking tape (figure 5.14). The sabots were then filled with different weights of sand (table 5.7).

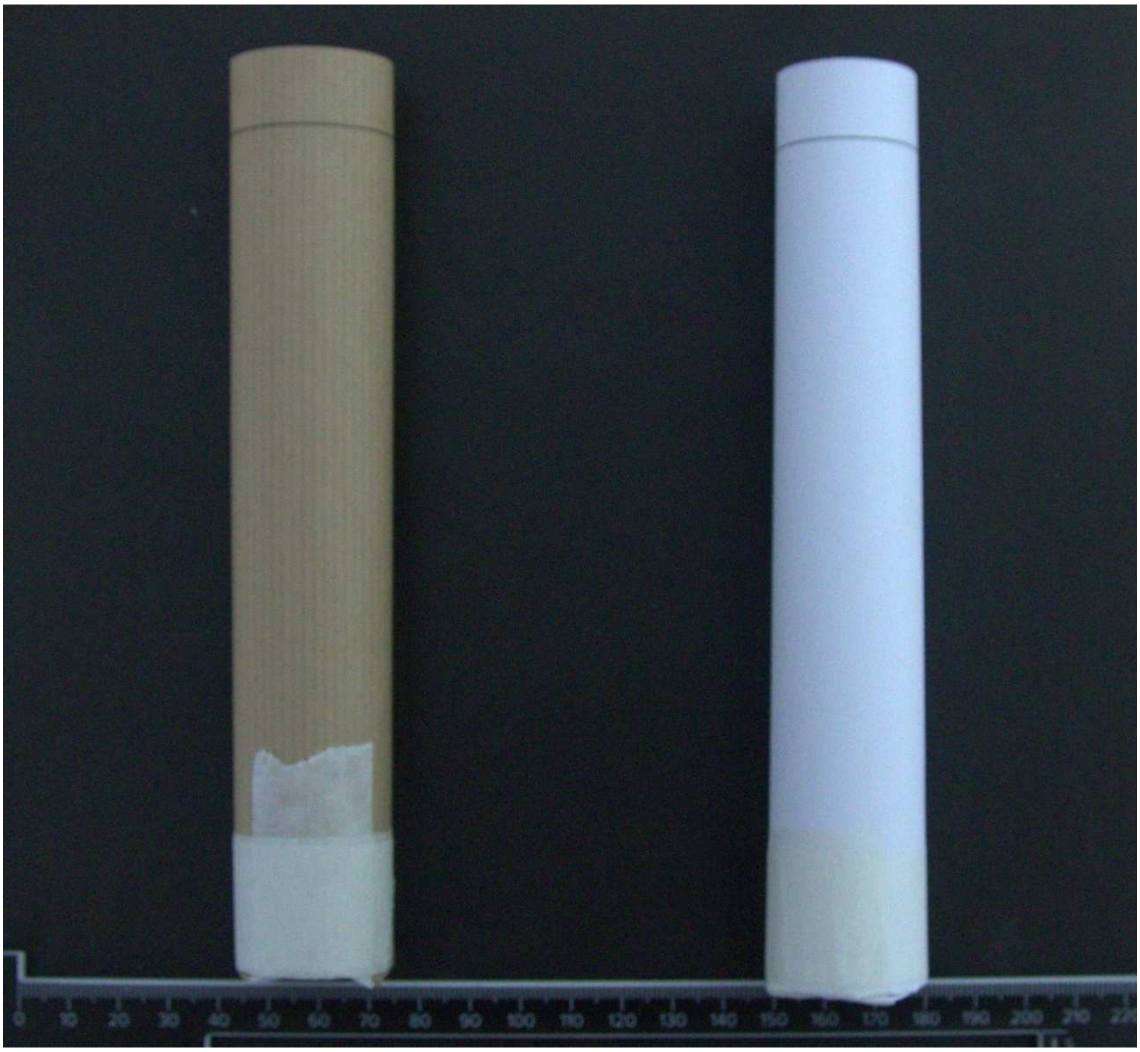


Figure 5.14: 160mm brown paper and white paper sabots

5.4.1.4 Preliminary test setup and method

The preliminary test setup and method used for part B remained the same for the testing in part C.

5.4.1.5 High speed video analysis

The method of high speed video analysis conducted in part B remained the same for the testing in part C.

Table 5.7: Test variable for 160mm and 180mm sabots

Length (mm)	Dimension (L x W) (mm x mm)	Weight of sand (g)
160	190x91	178
180	210x91	205

A – Sabot lengths

Distance (mm)	100
Propellant weight (g)	40
Target	No target; Plate
Sand	Dry
Sabot	160mm and 180mm sabots; Brown paper (BP); White paper (PP)
Load cell	9051A load washer via PicoScope 3000 connected to PicoScope oscilloscope software

B – Variables

5.4.2 Results and discussion

Three trials were conducted for each the Brown paper (BP) and the White paper (PP) for both of the sabot lengths (160mm and 180mm) at a distance of 100mm from the muzzle using a metal surrogate. The results are presented in table 5.8.

Table 5.8: Gun based test results for 160 and 180mm brown paper and white paper sabots

Sabot length (mm)	Velocity (m/s)		Peak force (kN)		Total impulse (N.s)	
	Brown paper (BP)	White paper (PP)	Brown paper (BP)	White paper (PP)	Brown paper (BP)	White paper (PP)
160						
Trial 1	627.0	56.5	188.6	DNR	111.6	10.1
Trial 2	619.7	656.3	191.4	185.6	110.3	116.8
Trial 3	601.8	472.3	189.5	164.8	107.1	84.1
180						
Trial 1	588.9	619.9	167.4	191.4	120.9	127.1
Trial 2	306.8	502.9	DNR	DNR	62.9	103.1
Trial 3	596.4	576.8	189.5	203.9	122.3	118.2

Based on these results it was decided to stop using the 180mm sabots for future trials, despite the fact that they produced consistent velocities (brown paper – mean: 592.7m/s, s.d.: 3.8m/s; white paper – mean: 566.5m/s, s.d.: 48.3m/s) and impulse (brown paper – mean: 121.6N.s, s.d.: 0.7N.s; white paper – mean: 116.1N.s, s.d.: 9.9N.s) when the propellant combusted properly; this was due to how close the loads produced were to the limit of the load cell; and hence care had to be taken to prevent damage to them. However, since the velocities (mean – 616.2m/s, s.d. – 10.6m/s) and impulse (mean – 109.7N.s, s.d. – 1.9N.s) produced by the 160mm brown paper sabots were consistent and impulse was close to the values recorded during the blast test (range: 111.7 – 196.4N.s), it was felt that this was a good candidate for further testing. Additionally, in almost all of the cases irrespective of 160mm or 180mm sabots and whether they were made from brown or white paper the loads measured were several times the lower limb threshold.

The cases where a lower velocity and lower loads were recorded (160mm – white paper – trial 1 and 3 and 180mm – brown paper – trial 2) were due to the way the sabot breaks up within the barrel. In these cases, the sabot would break up within the barrel and the sand would be projected as a stream rather than a focused mass. However, in the other cases the entire sabot would be shot out as a slug, producing loads and velocities that were quite different from the rest of the data.

In the cases where no data recorded (DNR) this was either due to the loads being too low or the connection between the load cell and the recording device being imperfect. To eliminate the possibility of a slug being formed the barrel was fitted with a sabot stripper consisting of a metal plate with a hole in the same diameter as the gun positioned in front of the muzzle to remove the sabot and outer material, however due to the loads produced being so high, it resulted in the sabot stripper being permanently bent out of shape and necessitating its removal. The following are stills captured from the high speed video that show the cases where a slug was not formed (figure 5.15) and where a slug was formed (figure 5.16).

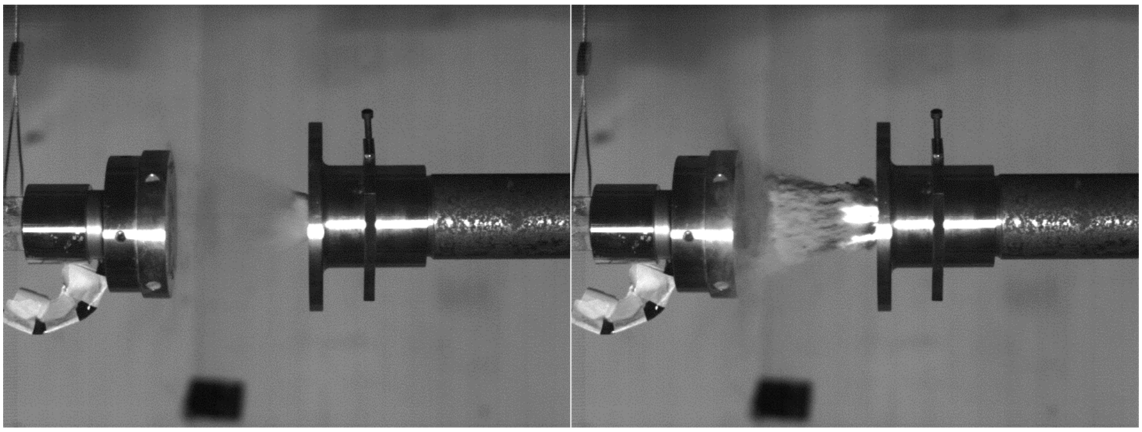


Figure 5.15: 160mm – White paper – Trial 1 – No slug formed

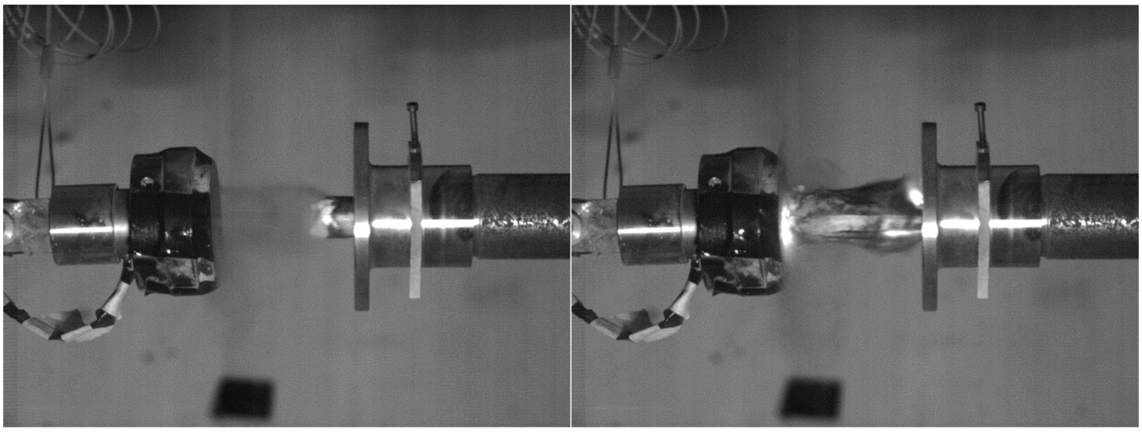


Figure 5.16: 160mm – Brown paper – Trial 1 – Slug formed

These trials suggest that the 160mm brown paper sabots when fired from a distance of 100mm are able to produce sufficiently high loads and velocities to be a replacement for blast testing. Further testing is required to see if the same is true when the distance is increased and when boots are used.

5.5 Part D – Testing 160mm sabots at different distances and propellant weights using a metal surrogate or a boot

For all of the previous experimental work all of the sabots were fired at a metal plate, hence part D describes the trials to determine the optimum distance at which the sabots would be able to penetrate boots that were fitted onto a metal surrogate.

For the purpose of these trials it was decided to start shooting the samples at an arbitrary distance of 650mm and move down from there, to the distance at which penetration is produced and loads measured are in line with those seen in the blast tests. The reason it was started at 650mm was because the high speed video showed beyond a metre the spread of the sand cloud was too large and that it would not be able to produce the loads at that distance. 650mm was sufficiently far away that it would be still able to produce the loads needed to produce penetration since the loads measure at 100mm was at the upper limit of the load cell.

For these trial 160mm brown paper (BP) sabots were fired at either the face of a metal surrogate or a Dunlop Wellington boots (DWB) and Lowa desert elite’s (LDE) fitted onto the metal surrogate limb at a starting distance of 650mm and moving down.

The reason it was decided to only use brown paper (BP) sabots was because it was observed that the cases of sand slugs forming was more prevalent and repeatable than in the trials using the white paper. This is not an issue since from the data it can be observed that the loads for either the brown (mean = 189.3kN, s.d. = 1.2kN) or white paper (mean = 178.5kN, s.d. = 11.1kN) are quite close to the limit of the load cell (200kN). Additionally, the velocities recorded by the 160mm brown paper sabots (mean = 616.2m/s, s.d. = 10.6m/s) were more consistent than the white paper sabots (mean = 395.0m/s, s.d. = 250.9m/s).

The propellant weight was also varied since in a few of the previous trials it was observed from the video and from remnants on the floor and in the cartridge case indicated that the propellant did not always fully burn which could be due to the large propellant weight and not enough sand weight sitting in front of it due to which there would not be sufficient back pressure developed resulting in the sand being fired before the propellant was completely burnt up.

5.5.1 Materials and methods

5.5.1.1 Test rig

The test rig used in part B, and the methods by which they were assembled remained the same for the testing in part D. The boots were fitted onto the metal surrogate and secured.

5.5.1.2 Sand

The sand used in part B, and the methods by which they were produced remained the same for the testing in part D.

5.5.1.3 Sabot

One type of paper was used to make sabots: brown wrapping paper (BP). The paper was cut into the appropriate dimensions to get sabots of the required length. The sabots were made by wrapping around a brass cylinder and sealing it at the bottom and along the vertical seam using commercial masking tape. The sabots were then filled with required weight of sand (table 5.9) and the tops were sealed by folding them securely. This was done to allow the sand to easily escape when the sabots were shot.

Table 5.9: Sabot dimensions and sand weight for 160mm brown paper sabots

Length (mm)	Dimension (L x W) (mm x mm)	Weight of sand (g)
160	190x91	178

5.5.1.4 Preliminary test setup and method

The sabots were fitted into a Rarden shell for firing. 40g or 30g of N160 propellant was used to get the different velocities using 160mm brown paper (BP) sabots sizes containing a known weight of sand. The sabots were fired from using 30mm barrel. The target for these sets of trials was the metal surrogate limb used for the blast tests or a boot fitted onto it which was connected to the rig and placed 400 – 650mm from the end of the muzzle.

Table 5.10: Test variables for gun based testing using brown paper sabots at different distances and different propellant weight against different targets

Distance (mm)	650, 600, 500, 400
Propellant weight (g)	40, 30
Target	Metal plate, Dunlop Wellington boots (DWB), Lowa desert elite (LDE)
Sabot	Brown paper (BP)
Load cell	9061A load washer via type 5017B charge amplifier connected to IMATEK c3008 data acquisition system

The same Kistler 9061A (range 0 – 200kN) load washer was placed in between the metal plate and the rig, which was connected to a Kistler type 5017B multichannel charge amplifier with the data being recorded in ImpacqtV3 software. For the first set of trials no high speed video was recorded, hence there were not any velocities being recorded.

5.5.2 Results and discussion

Twelve trials were conducted for using 160mm brown paper sabots; 11 were using a 40g propellant and 1 was using a 30g propellant, at distances of 400 – 650mm from the muzzle using a metal surrogate or two different boot types (table 5.11).

Table 5.11: Result of gun based test using paper sabots at varying distances

Trial no.	Propellant (g)	Distance (mm)	Target	Peak load (kN)	Penetration (Yes/No)
1	40	650	Plate	74.2	NA
2	40	650	Plate	48.6	NA
3	40	650	Plate	155.2	NA
4	40	650	Plate	169.1	NA
5	40	650	Plate	165.5	NA
6	40	650	DWB – Metal surrogate	123.6	No
7	40	650	LDE – Metal surrogate	145.3	No
8	40	650	LDE – Metal surrogate	170.0	Yes
9	30	650	LDE – Metal surrogate	129.8	Yes
10	40	600	Plate	119.4	NA
11	40	500	Plate	173.6	NA
12	40	400	Plate	201.8	NA

Based on these results the data suggested that there was another factor that determines the loads produced and whether penetration occurs. This was based on two observations; the first being that when all the variables were fixed the loads measured varied quite significantly as was the case in the first five trials where three trials produced loads in excess of 150kN and the rest produced loads below 75kN. The second observation was based on the results of the 7^{th} and 8^{th} trial where for the same conditions one was able to produce penetration (8^{th} trial) and the other was not (7^{th} trial). Interestingly when comparing the 7^{th} and the 9^{th} trial; where all the conditions are the same other than the propellant weight, it can be seen that penetration occurs when moving to a lower propellant weight of 30g (9^{th} trial) despite being a lower load that is measured. This suggests that in these trials it is not the loads measured that determines the penetration but rather some other factor. The hypothesis here based on these trials and the observations made in the previous experiments is that it is the shape of the sand that is shot out of the barrel or rather if the sand comes out as a slug or not that determines penetration with the loads only being a secondary factor.

5.6 Part E – Determining the cause of penetration when using 160mm paper sabots

Part E describes the trials that were undertaken to prove the hypothesis that the shape of the sand determines penetration rather than the load.

From the previous table (table 5.11) it can be seen that even at 500mm the loads measured are quite high, hence it was decided to fix the distance at which the sabots were shot at to 500mm. It was decided to use a 30g propellant for the testing since from the previous table it can be seen that at 650mm this propellant weight was able to produce penetration. To simplify the testing, the sabots were fired at either a metal plate or Dunlop Wellington boots (DWB).

In summary for these trials 160mm brown paper (BP) sabots were fired using a 30g propellant weight at either the face of a metal surrogate (PLATE) or a Dunlop Wellington boots (DWB) fitted onto the metal surrogate limb at a distance of 500mm.

5.6.1 Materials and methods

5.6.1.1 Test rig

The test rig used in part B, and the methods by which they were assembled remained the same for the testing in part E. The boots were fitted onto the metal surrogate and secured.

5.6.1.2 Sand

The sand used in part B, and the methods by which they were produced remained the same for the testing in part E.

5.6.1.3 Sabot

The sabot used in part D and the method in which it was prepared remained the same in part E.

5.6.1.4 Preliminary test setup and method

The sabots were fitted into a Rarden shell for firing. 30g of N160 propellant was used to fire 160mm brown paper (BP) sabots sizes containing a known weight of sand. The sabots were fired using 30mm barrel 1135mm long. The target for these sets of trials was the metal surrogate limb or a boot fitted onto it which was connected to the rig and placed 500mm from the end of the muzzle.

Table 5.12: Test variables for gun based test to determine the cause of penetration

Distance (mm)	500
Propellant weight (g)	30
Target	Metal plate, Dunlop Wellington boots (DWB)
Sabot	Brown paper (BP) – 160mm
Load cell	9061A load washer via type 5017B charge amplifier connected to IMATEK c3008 data acquisition system

The impact events were recorded using a Phantom high – speed video camera (V12) (10000 fps, 6μs exposure time and 1280 x 480 resolution) and illuminated using two 2kW halogen lights. The loads were recorded using a Kistler 9061A (range 0 – 200kN) load washer placed between the metal plate and the rig, which was connected to a Kistler type 5017B multichannel charge amplifier with the data being recorded in ImpacqtV3 software.

From the high speed video, a record was also made in regards to the shape of the sand, whether it was a slug or not.

5.6.2 Results and discussion

14 trials were conducted, 6 using the metal surrogate without a boot and 8 using the Dunlop Wellington boot (DWB) fitted onto the metal surrogate (table 5.13).

Table 5.13: Result of gun based testing to determine cause of penetration

Trial no.	Propellant (g)	Distance (mm)	Target	Peak load (kN)	Velocity (m/s)	Penetration (Yes/No)	Slug (Yes/No)
1	30	500	Plate	77.7	553.7	NA	No
2	30	500	Plate	134.7	407.5	NA	Yes
3	30	500	Plate	128.4	361.0	NA	Yes
4	30	500	Plate	157.6	337.0	NA	Yes
5	30	500	Plate	133.4	433.2	NA	Yes
6	30	500	Plate	122.6	318.5	NA	Yes
7	30	500	DWB – Metal surrogate	100.8	340.7	Yes	Yes
8	30	500	DWB – Metal surrogate	74.4	460.1	No	No
9	30	500	DWB – Metal surrogate	118.0	304.7	Yes	Yes

10	30	500	DWB – Metal surrogate	101.4	330.3	Yes	Yes
11	30	500	DWB – Metal surrogate	70.3	439.2	No	No
12	30	500	DWB – Metal surrogate	65.5	411.5	No	No
13	30	500	DWB – Metal surrogate	109.9	362.0	Yes	Yes
14	30	500	DWB – Metal surrogate	101.6	360.5	Yes	Yes

Looking at the entire set of data and comparing the cases where higher loads were recorded against the cases where the lower loads were recorded, the high speed video clearly shows the sand being shot in the shape of a slug for the cases with the higher loads. Over the distance of 500mm the slug breaks down and takes the approximate shape of a cone; with all the loads being focused on a smaller area (figure 5.17).

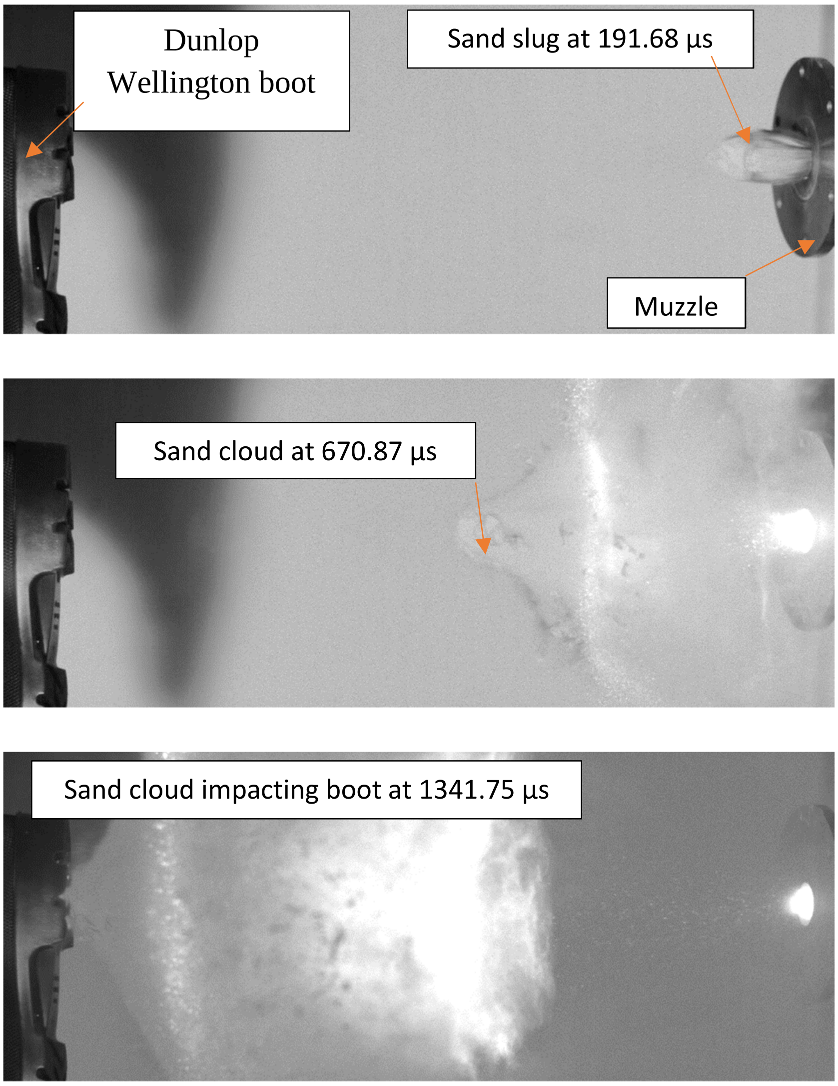


Figure 5.17: A – Slug exits the barrel; B – Slug takes the shape of a conical sand cloud with defined borders; C – Sand cloud impacts the target (A to C; Top to Bottom)

An entirely different thing occurs when the sand doesn't come out in the form of a slug (figure 5.18); with the sand being spread out over a larger area, hence no focused point of contact with the target.

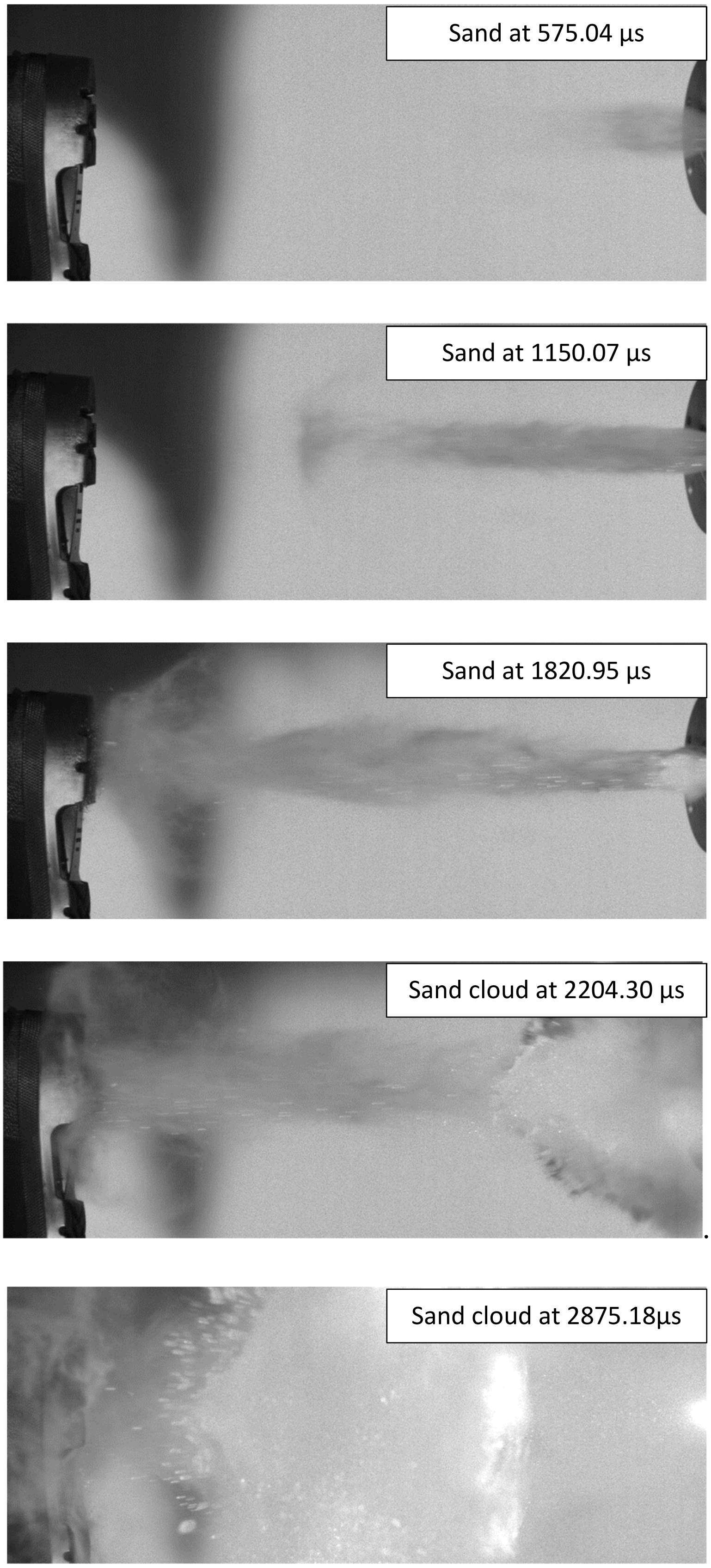


Figure 5.18: Absence of sand slug and delayed formation of a sand cloud with a larger area

The reason this phenomenon was not observed in part B or C of the trials was that they were conducted over a much shorter distance and not giving the sand a chance to spread out, and hence focusing on a much smaller area.

Analysis of variance (ANOVA) was used to determine if the formation of the slug and the target had a significant effect on the loads recorded. The formation of a slug had a highly significant effect on the loads measured ($F_{1, 10}$ = 52.06, $p \leq 0.001$) (table 5.14B). The mean load (mean = 120.8kN, s.d. = 18.4kN) (table 4.12A) in the cases with the slug being produced was over 40kN higher than the cases in which they are not formed (mean = 71.9kN, s.d. = 5.3kN) (table 5.14A). The target had a significant effect on the loads recorded ($F_{1, 10}$ = 7.94, $p \leq 0.05$) (table 5.14B). The mean load (mean = 125.7kN, s.d. = 26.4kN) in the cases when the plate was used was over 30kN higher than the cases in which Dunlop Wellington boots was used. The slug – target interaction did not have a significant effect on the loads measured ($F_{1, 10}$ = 2.69, $p > 0.05$) (table 5.14B). This is because the slug always resulted in higher loads measured irrespective of the target. However, the magnitude by which the force measured increased was greater for the plate target when a slug was formed. Normality of data and equality of variance was checked for each data set.

Table 5.14: Analysis of variance of gun based test for all samples using paper sabots evaluating slug and target effect on loads

Slug (Yes/No)	Target	Mean load (kN)	Standard deviation (kN)	N
No	DWB	70.0	4.5	3
	Plate	77.7		1
	Total	71.9	5.3	4
Yes	DWB	106.3	7.5	5
	Plate	135.4	13.4	5
	Total	120.8	18.4	10
Total	DWB	92.7	19.8	8
	Plate	125.7	26.4	6
	Total	106.9	27.7	14

A – Selected descriptive statistics

Source of variation	SS	d.f.	Mean square	F	Sig.	P≤
Slug Yes/No	5093.07	1	5093.07	52.06	0.000	0.001
Target	776.26	1	776.26	7.94	0.018	0.05
Slug Yes/No * Target	263.09	1	263.09	2.69	0.132	
Error	978.30	10	97.82			

B – Analysis of variance for loads produced

Analysis of variance (ANOVA) was used to determine if the formation of the slug and the target had a significant effect on the velocity recorded. The formation of a slug had a highly significant effect on the velocities recorded ($F_{1,12} = 16.69$, $p \leq 0.005$) (table 5.15B). The mean velocities (mean = 355.0m/s, s.d. = 41.8m/s) (table 5.15A) in the cases with the slug being produced was over 100m/s lower than the cases in which they are not formed (mean = 466.1m/s, s.d. = 61.7m/s) (table 5.15A). Normality of data and equality of variance was checked for each data set.

Table 5.15: Analysis of variance for gun based test for all samples using paper sabots evaluating slug effect on velocities

Slug (Yes/No)	Velocity (m/s)		N
	Mean (m/s)	Standard deviation (m/s)	
Yes	355.0	41.8	4
No	466.1	61.7	10

A – Selected descriptive statistics

Source of variation	SS	d.f.	Mean square	F	Sig.	p≤
Slug	35294.09	1	35294.09	16.67	0.001	0.005
Error	25407.81	12	2117.32			

B – Analysis of variance for velocities recorded

When looking at the data only for the Dunlop Wellington boots DWB; the formation of a slug had a highly significant effect on the loads produced ($F_{1,6} = 55.80$, $p \leq 0.001$) (table 5.16B). The mean load (mean = 106.3kN, s.d. = 7.5kN) (table 5.16A) in the cases with the slug being produced was over 30kN higher than the cases in which they are not formed (mean = 70.0kN, s.d. = 4.5kN) (table 5.16A). Normality of data and equality of variance was checked for each data set.

Table 5.16: Analysis of variance for gun based test for Dunlop Wellington boots using paper sabots evaluating slug effect on loads

Slug (Yes/No)	Peak load (kN)		N
	Mean (kN)	Standard deviation (kN)	8
Yes	106.3	7.5	5
No	70.0	4.5	3

A – Selected descriptive statistics

Source of variation	SS	d.f.	Mean square	F	Sig.	p≤
Slug	2470.85	1	2470.85	55.80	0.00	0.001
Error	265.67	6	44.28			

B – Analysis of variance for loads produced

Since the ANOVA test shows that the formation of the slug has significant effect over the loads measures and the velocities recorded, and since penetration occurs only when a slug is formed, it is necessary to design the gun based test to form a slug every time. Since the formation of the slug influences the area upon which the sand cloud acts, it influences the impulse per unit area values.

Table 5.17: Average velocity of the sand cloud when a slug is and is not formed

Slug (Yes/No)	Velocity (m/s)	
	Mean (m/s)	Standard deviation (m/s)
Yes	355.5	39.4
No	466.1	61.7

From table 5.17, the average velocity of the sand cloud is known for both when slugs are formed and when they are not. Since the weight of the sand (178g) contained in the sabots is known from earlier, it is possible to calculate the total impulse of the sand cloud. The total impulse calculations are as follows;

Total impulse, I = mv

Total impulse when slug is formed, I = 0.178 x 355.53 = 63.3N.s

Total impulse when slug is not formed, I = 0.178 x 466.11 = 83.0N.s

Despite the fact that when no slug is formed the total impulse is greater than when the slug is formed but no penetration occurs indicates that the area over which the sand cloud acts plays an important role. This is why the impulse per unit area calculation is more indicative of the performance of the gun based test. Since the sand cloud assumes the shape of a cone as seen from the high speed images it is necessary to determine the diameter of the cone, since it determines the area of the boot over which the sand cloud acts. When a slug is not formed the diameter of the sand cloud is so large that its outer boundaries is not captured by the high speed camera, hence it can be assumed that it acts over the entire surface area of the sole. However, when a slug is formed the surface area over which the sand cloud acts is much smaller.

For a size 11 LDE boot, the area of the sole was calculated using the ImageJ software using the measurement tool to calculate the area. When no slug is formed the impulse per unit area calculations are as follows:

Total impulse when slug is not formed, I = 83.0N.s

Area of the sole for the blast test, A = $0.022m^2$

Hence, impulse per unit area = I/A = $3771.3N.s/m^2$

When a slug is formed, the diameter of the cone was estimated to be 196.6mm which exceeded the width of the heel (80mm) (figure 5.19)

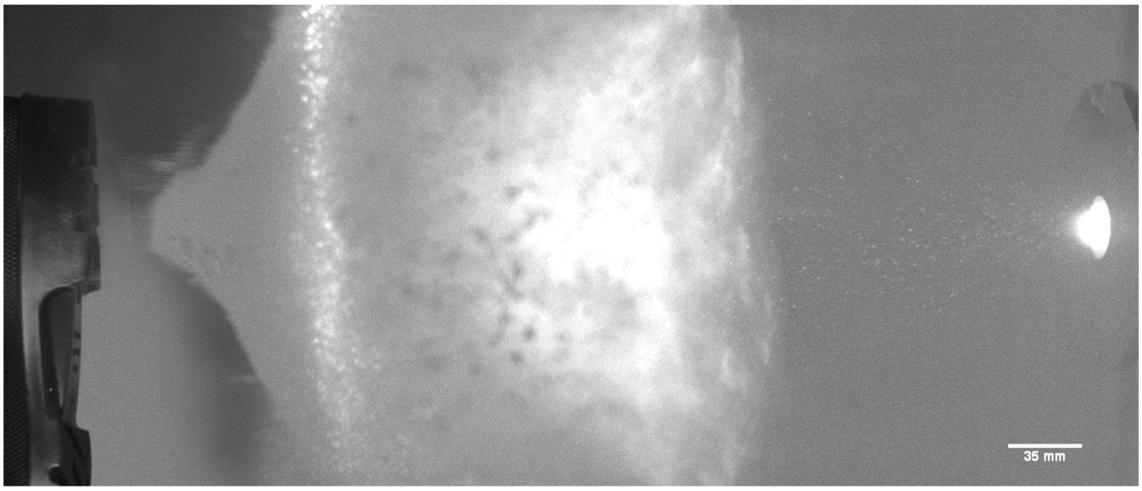


Figure 5.19: Sand cloud with conical shape just before impacting the boot using paper sabots

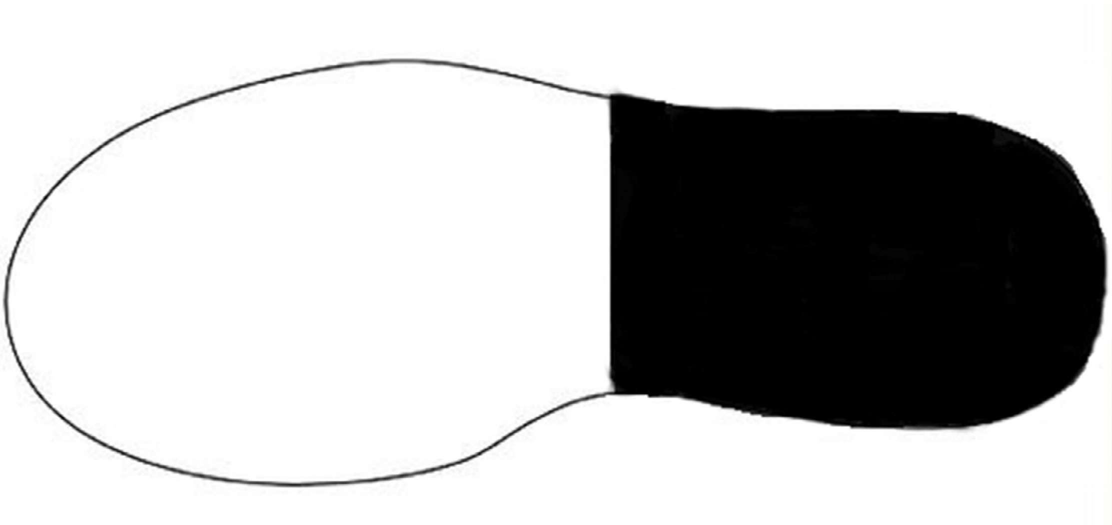


Figure 5.20: Surface area over which the sand cloud acts when slug is formed

The area impacted by the sand cloud extends 91.8mm from the centre of the heel and this area was calculated using the ImageJ software (figure 5.20). When a slug is formed the impulse per unit area calculations are as follows:

Total impulse when slug is formed, I = 63.3N.s

Area of the sole for the blast test, $A = 0.01m^2$

Hence, impulse per unit area = $I/A = 6330N.s/m^2$

The energy and energy per unit area values can be calculated based on the values used above as was previously done for the blast tests;

Total energy release from propellant = Energy per kilogram x weight of propellant

For 30g N160, E = energy per kg x weight of propellant

= 3.650 x 0.030 = 0.109MJ

Energy of the sand cloud can be calculated as follows;

Weight of sand (m) = 0.178kg

Hence,

Energy when slug is not formed, $E = 0.5mv^2 = 19.3KJ$

Energy when slug is formed, $E = 0.5mv^2 = 11.3KJ$

Since the area over which the sand cloud acts for both when a slug is formed and when it is not, is known, it is possible to calculate the energy per unit area.

When slug is not formed,

Area of the sole over which the sand cloud acts (A) = $0.022m^2$

Energy per unit area, $E/A = 19.336/0.022 = 879.0KJ/m^2$

When slug is formed,

Area of the sole over which the sand cloud acts (A) = $0.01m^2$

Energy per unit area, $E/A = 11.3/0.01 = 1130KJ/m^2$

As can be seen the energy and energy per unit values of the gun based trials for both slug and non – slug cases are greater than those observed during the blast test despite the fact that the blast test resulted in quite significant damage to the boot and resulted in penetration most of the time. This is due to the much higher velocities that can be achieved in the gun based test by changing the charge size as examined in section 5.4 and 5.6 (table 5.8 – 160mm sabots and table 5.13) and the smaller area over which the sand cloud acts.

The impulse per unit area performance of the sand cloud is lower than the blast tests when no slug is formed. However, when a slug is formed the value is higher than that estimated for the blast test using the Tremblay equation, but is still lower than the values estimated using both the high – speed video and the force – time curve. This means that it is possible to achieve penetration of the boot at a much lower impulse per unit area than the values from the blast test, and hence cause tissue damage, provided a slug is formed every time. However, the event of the slug formation is entirely unpredictable, despite the best efforts to eliminate variables and minimize human errors. Hence, an alternate method was required that would be able to produce the loads and the impulse per unit area values that were observed when using the brown paper (BP) sabots, and hence produce penetration consistently.

5.7 Part F – A replacement for paper sabots

Part F describes the experimental trials that were undertaken to find an alternate solution to paper sabots while producing the same loads and velocities. Since during part C production of slugs was identified as an issue; while conducting trials in part D a single trial was conducted by loading the sand directly into the case and firing it at the target using 30g of propellant which resulted in loads of 193kN. However, this idea was discarded since it resulted in the failure of the case, and hence no repeats were performed. part E revisits the idea by conducting trials using different iterations of the case to address the issues observed in previous trials.

5.7.1 Materials and methods

5.7.1.1 Test rig

The test rig used in part B, and the methods by which they were assembled remained the same for the testing in part F. The boots were fitted onto the metal surrogate and secured.

5.7.1.2 Sand

The sand used in part B, and the methods by which they were produced remained the same for the testing in part F.

5.7.1.3 Case

The trials went through three different iterations of the case addressing the limitations of the previous one in each of the subsequent iterations (figure 5.24). The first one was the Rarden shell that was used previously in the trials.

The second case was a brass cylindrical case with the same dimensions as the standard case but with a cylindrical section down the middle without the taper (figure 5.24) of the Rarden shell (figure 5.21). The sand was loaded directly into the cylinder without a sabot. This was to eliminate the shaping effect the sabot had on the sand cloud.

Figure 5.21: Fabricated brass cylindrical case

The third was a stainless steel cylindrical case with the same dimensions as the brass cylindrical case but milled with tighter margins so that it had a more accurate fit in the barrel leaving no room for expansion (figure 5.22 and 5.23). Similarly, to the brass cylindrical case the sand was loaded directly into it.

Figure 5.22: Fabricated steel cylindrical case

Figure 5.23: Hollow fabricated steel cylindrical case

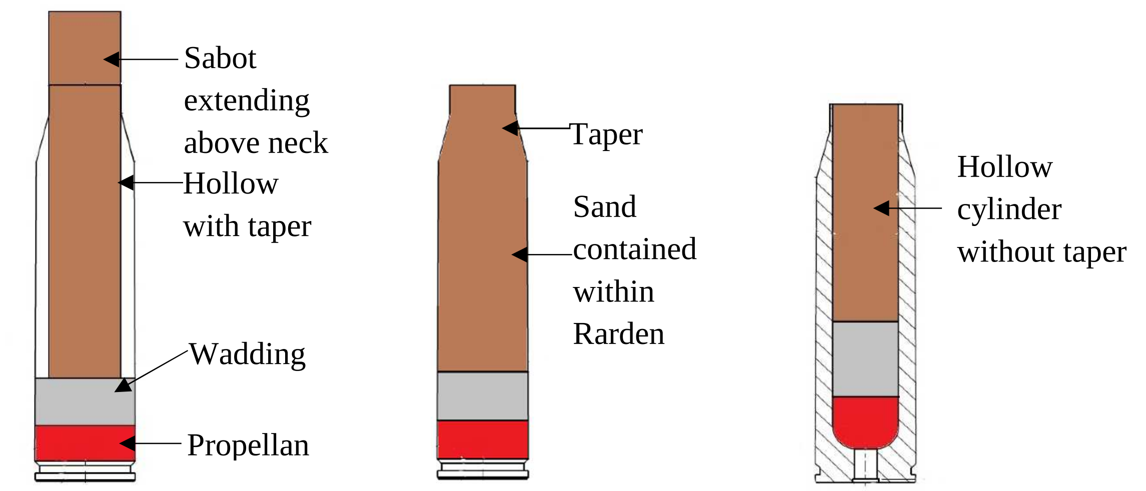


Figure 5.24: Different cases with different methods of sand loading i) Rarden shell with sabot, ii) Rarden shell with sand directly loaded and iii) Brass/steel cylindrical case

5.7.1.4 Gelatine surrogate

The method used in chapter 4, part B to prepare the gelatine surrogates remained the same for the testing in part E.

5.7.2 Preliminary test setup and method

20g or 30g of N160 propellant was weighed into the case which was then loaded with the required weight of sand. Wadding was then added to the top and tamped down and the case was sealed on the top with a small piece of adhesive tape. The case was fired using a 30mm barrel. The target for these sets of trials was either i) metal surrogate, ii) Dunlop Wellington boot (DWB) on a gelatine surrogate, iii) Dunlop Wellington boot (DWB) fitted onto a metal surrogate or iv) Lowa desert elite’s fitted onto the surrogate limb. The target was placed 500mm from the end of the muzzle (table 5.18).

Table 5.18: Test variables for gun based testing using different cases

Distance (mm)	500	
Case	Standard	Brass/Steel
Propellant weight (g)	20	30
Target	Metal surrogate, gelatine surrogate, Dunlop Wellington boot (DWB) or Lowa desert elites (LDE) fit onto surrogates	
Sand (g)	150	50
Load cell	9051A load washer via type 5017B charge amplifier connected to IMATEK c3008 data acquisition system	

The impact events were recorded using a Phantom high – speed video camera (V12) (10000 fps, 6μs exposure time and 1280 x 480 resolution) and illuminated using two 2kW halogen lights. The loads were recorded using a Kistler 9061A (range 0 – 200kN) connected to a Kistler type 5017B multichannel charge amplifier with the data being recorded in ImpacqtV3 software. From the high speed video, a record was also made in regards to the shape of the sand, whether it was a slug or not.

5.7.3 Results and Discussion

This section is split into three parts i) Using standard case, ii) Using brass cylindrical case and iii) Using steel cylindrical case.

5.7.3.1 Part I – Rarden shell

The results of the trials of the standard case using 20g propellant weight at a distance of 500mm is given in table 5.19.

Table 5.19: Result of gun based testing using Rarden shell with sand loaded directly in the shell

D – Distance of target V – Velocity

Trial no.	Propellant (g)	D (mm)	Target	Peak load (kN)	V (m/s)	Penetration (Yes/No)	Slug (Yes/No)	Case intact (Yes/No)
1	20	500	Plate	177.8	486.2	NA	Yes	Yes
2	20	500	Plate	205.3	697.6	NA	Yes	Yes
3	20	500	Plate	69.4	225.8	NA	No	No
4	20	500	Plate	26.2	337.0	NA	No	No
5	20	500	Plate	22.0	453.0	NA	No	No
6	20	500	DWB – Gelatine	11.4	435.0	No	No	Yes
7	20	500	DWB – Gelatine	4.0	200.3	No	No	No
8	20	500	DWB – Gelatine	7.0	243.2	No	No	Yes

A single pre – trial test was conducted using 30g of propellant which, resulted in the case undergoing failure along its width after only one shot. This is why the propellant weight was reduced from 30g from previous trials to 20g.

In the first two repeats (table 5.19), slugs were observed when firing at the metal surrogate, resulting in loads (mean = 191.6kN, s.d. = 13.8kN) close to the limit of the load cell (200kN) and exceeding those observed using paper sabots (mean = 135.3kN, s.d. = 11.9kN) (table 5.13) against the metal plate when slugs were formed. For the rest of the trials no slugs were observed resulting in lower loads measured. As observed in chapter 4, the loads measured are dependent on the surrogate used, with much lower loads being measured in the case of the gelatine surrogate when compared to metal surrogate. The same is true in this case when the loads measured against gelatine surrogate were much lower than those against a metal surrogate irrespective of whether the case underwent failure. No slugs were observed in the trials against Dunlop Wellington boots with gelatine surrogates, and hence no penetration was observed which is in line with the observations made in part E.

Failure still occurs frequently for 20g propellant weight when the same case is used multiple times and in some cases on the first shot. The reason for this is most likely the bottle neck at the neck of the case where the sand can't get out of the case fast enough, resulting in pressure being build inside the case due to the expanding gases leading to failure. The reason only 150g of sand was used was because it was not possible to fit the 178g of sand used in the paper sabot trials and fit in wadding on top of that. 150g of sand is close enough to the 178g mark to be able to cause the penetration and the tissue damage.

5.7.3.2 Part II – Brass cylindrical case

Due to the frequency at which failure occurs in the cases and the inability to produce slugs consistently it was decided to move to a brass cylindrical case with a hollow cylindrical section. The cylindrical section ensures that there is not any bottle neck and that the sand will be ejected smoothly. The brass cylindrical case was designed such that it was able to easily hold 50g of sand in addition to the propellant and wadding and was sealed on the top using duct tape to ensure that the sand slugs are formed. A single trial was conducted using it which resulted in failure of the case which was estimated to be due to the expansion of the case in the barrel during the trial (figure 5.25)

Figure 5.25: Brass cylindrical case used in gun based tests showing failure

5.7.3.3 Part III – Steel cylindrical case

To overcome this the material from which the case was fabricated was changed from brass to steel with stricter control on dimensions leaving much less room for expansion in the barrel during the trials. The dimensions of the case remained the same with the same capacity for sand and propellant weight.

The results of the trials of the steel cylindrical case at a distance of 500mm is given in table 5.20.

Table 5.20: Results of gun based test using steel cylindrical case with sand loaded directly into the case

Trial no.	Propellant (g)	Distance (mm)	Target	Peak load (kN)	Velocity (m/s)	Penetration (Yes/No)	Slug (Yes/No)
1	20	500	Plate	205.9	656.3	NA	Yes
2	30	500	DWB – Gelatine	10.3	926.6	Yes	Yes
3	30	500	DWB – Gelatine	9.0	978.6	Yes	Yes
4	30	500	DWB – Gelatine	9.8	991.2	Yes	Yes
5	30	500	DWB – Gelatine	9.8	912.5	Yes	Yes
6	30	500	DWB – Gelatine	11.5	988.0	Yes	Yes
7	30	500	DWB – Gelatine	9.8	966.3	Yes	Yes
8	30	500	LDE – Plate	205.6	938.6	Yes	Yes
9	30	500	DWB – Plate	205.9	966.3	Yes	Yes
10	30	500	DWB – Plate	205.9	994.9	Yes	Yes

11	30	500	DWB – Plate	205.9	951.0	Yes	Yes
12	30	500	DWB – Plate	205.9	935.6	Yes	Yes
13	30	500	ALT – Plate	205.9	917.5	Yes	Yes

For these trials it was decided to use 30g of propellant to reproduce the blast tests from chapter 4. All of these trials were conducted using the same amount of wadding and the case was sealed using duct tape at the top. As can be seen from the table, slugs were produced in all of the cases and penetration was observed where applicable. The velocities produced for all the 30g propellant trials was very consistent (mean = 955.6m/s, s.d. = 28.1m/s) and shows that the method is very reproducible. As expected the loads measured in the trials where a gelatine leg was used was much lower (mean = 10.0kN, s.d. = 0.8kN) than where a plate was used (mean = 205.8kN, s.d. = 0.1kN). This is due to the fact that the gelatine legs lack any supporting structure to transfer the loads completely to the load cell before they are destroyed, while on the other hand the loads measured using the plate is the upper threshold of the load cell; hence it cannot measure a value more than that. This again shows that the loads measured are very dependent on the surrogate used during the trials, and hence for the future work, loads will not be measured since they are not a true indicator of the damage done to the leg when gelatine surrogates are used.

From the above table (5.20), it can be seen that a slug was formed in every case. Since the average velocity of the sand cloud is known along with the weight of the sand, it is possible to calculate the total impulse of the sand cloud. The total impulse calculations are as follows;

Total impulse, I = mv

Where,

Velocity, v = 955.6m/s

Mass, m = 0.05kg

Total impulse, I = 47.8N.s

As shown previously the impulse per unit area value is a good comparison of performance between different tests. For trials using the steel cylindrical case, the diameter of the sand cloud was 80.26mm which is approximately equal to the width of the heel (80mm) (figure 5.26).

Figure 5.26: Sand cloud with conical shape just before impacting the boot using steel cylindrical case

Since the cone has a diameter less than the width of the heel, it impacts the heel on an area having the dimensions of a circle with diameter equal to the cone.

Total impulse, I = 47.8N.s

Diameter of the sand cloud, d = 80.26 mm = 0.08m

Area of the sole for the blast test, $A = \pi d^2/4 = 0.005m^2$

Hence, impulse per unit area = I/A = $9556N.s/m^2$

The energy and energy per unit area value can be calculated using previous values, since the weight of the sand and the velocity of the sand cloud is known.

Weight of sand (m) = 0.05kg

Velocity of the sand cloud (v) = 955.6m/s

Hence, Energy, $E = 0.5mv^2 = 22.8KJ$

Since the weight of the PE4 and N160 powder used in the blast and gun based test are known, the theoretical energy output can be calculated;

Energy release from explosive charge = Energy per kilogram x weight of charge

For 20g PE4, E = energy per kg x weight of charge

= 5.621 x 0.020 = 0.112MJ

For 30g N160, E = 3.650 x 0.030 = 0.109MJ

As can be seen from the above calculation, despite the blast and the gun based tests having almost similar energy output from the charges used, the energy that is imparted to the sand is quite different with the blast tests having an energy output of 6.4KJ compared to 22.8KJ from the gun based test. This is probably due to the weight of the sand that has to be moved by the blast event which is 3kg in the case of the blast trials compared to 0.05kg in the case of the gun based trials. Hence, comparison of energy is not a suitable means of comparing the performance of the two tests.

For the steel cylindrical case gun based tests, the energy per unit area can be calculated as follows;

Area of the sole over which the sand cloud acts (A) = 0.005m^2

Energy per unit area, E/A = 22.829/0.005 = 4565.8kJ/m^2

As can be seen, the energy calculated from the velocity of the sand for the blast (6.4KJ) is lower than the gun based test using paper sabots (11.3KJ) despite the fact that the blast test resulted in quite significant damage to the boot and resulted in penetration most of the time. However, the energy of the gun based test for the steel cylindrical case (22.8KJ) is double the energy of the gun based test using the paper sabots (11.3KJ) and the Rarden shell. This is to be expected, since the purpose of designing the steel cylindrical case was to increase the penetration potential of the sand by producing slugs consistently, thereby increasing its velocity and decreasing the spread of the sand cloud. While, this shows that the gun based test using the steel cylindrical case is able to produce a sand cloud that has a lot more energy than the other tests over a smaller area, the energy and energy per unit area difference between the 160mm paper sabots and steel cylindrical case trails are so large that it cannot be used as a means to assess the performance of the different tests. This is because while impulse is a function of velocity, energy is a function of velocity squared. And hence for a blast test where the velocity recorded was lower (65.1m/s) it would result in a lower energy calculation compared to the gun based test where the velocities recorded were much higher (955.6m/s).

The gun based tests showed that using paper sabots was generally unreliable with respect to whether a slug was formed. This is reflected in the impulse per unit area calculation, where the impulse per unit area from the gun based test falls below that of the blast test when a slug is not formed resulting in no penetration. The purpose of moving towards the steel cylindrical case as a mechanism for firing the sand was to produce more consistent result by producing slugs formed every time and at a higher velocity in addition to the sand having a higher concentration over a smaller area. This is reflected in the impulse per unit area calculations from the steel cylindrical case which exceeds the impulse per unit area of both the blast test and the gun based tests using paper sabot. Hence, the impulse per unit area is a more accurate estimation of the performance of the test (blast and gun based) where the higher the impulse per unit area, the more reliable the test is with a higher chance of penetration. This lines up which the observation made by Fujinaka et al. (1966) which identifies the impulse per unit area as a significant factor which determines the performance of the boot. The lower the impulse per unit area, the lesser chance of the boot being penetrated. This is one of the reasons that a wedge shaped sole works quite well in a blast boot, where in addition to increasing the standoff distance its able to increase the surface area over which the total impulse acts thereby reducing its potency. On the other hand, the total impulse doesn’t give a clear picture of the performance of both the tests since the total impulse of the blast tests exceeded that of the gun based test by a factor of at least three. Hence, it makes more sense to use the impulse per unit area over which the total impulse is acting.

In conclusion it can be seen that the new test methodology is able to produce repeatable and reproducible results matching the performance of the blast test in terms of impulse per unit area of the sand cloud and having a higher energy per unit area value. It is a much more efficient and economic testing process that is able to address the issues associated with blast testing and is able to produce the loads and the penetration that can be seen in the case of a blast test. However, it has to be kept in mind that these are only comparable as long as the variables remain the same and the surrogate used in each of the testing is the same.

Chapter 6: SOCKS AS A MECHANISM OF CONTAMINATION MITIGATION

6.1 Introduction

As discussed in chapter 4 and seen from the results in chapter 5, the loads measured during the blast and gun based test exceeds the lower limb fracture threshold by a large factor. The literature (Trimble et al, 2001) also identifies that contamination plays a role in the surgical outcome. If it is assumed that it is not possible to sufficiently reduce the loads transferred to the lower limb using boots without adversely affecting mobility, then the next logical step would be to minimize the contamination of the tissue during the blast event. This chapter looks at the possibility of using different types of socks to minimize contamination assuming that loads cannot be reduced further.

This chapter uses the test method that was developed in chapter 5 in order to fire sand at gelatine surrogates that were protected by using different socks.

6.2 Materials and methods

6.2.1 Test rig

The test rig used in chapter 5, and the methods by which they were assembled remained the same for the testing in chapter 6.

6.2.2 Sand

The sand used in chapter 4, and the methods by which they were produced remained the same for the testing in chapter 6.

6.2.3 Case

The steel cylindrical case used in chapter 4 was the same that was used in chapter 5.

6.2.4 Gelatine surrogate

The method used in chapter 4, part B to prepare the gelatine surrogates remained the same for the testing in chapter 6.

6.2.5 Socks

For the trials two different socks were used, i) Reebok[1] 20K cut resistant skate socks (figure 6.1) and ii) MOD issue tropical desert tan socks (figure 6.2)

6.2.5.1 Reebok 20K cut resistant skate socks

The reebok 20K protective skate socks are the premier skate socks in the Reebok line. The 20K socks offer protection against cuts and abrasions, are comfortable and fight odour with hygienic properties. A flat knit construction reduces bulk and eliminates bunching.

The 20K socks feature Dyneema®, which is a low – weight and abrasion resistant fibre. The socks also have copper fibres woven into them, which the manufacturer claims, reduces bacterial growth.

Composition: 52% Dyneema, 25% polyester – copper blend, 20% polyester and 3% elastane.

Figure 6.1: Reebok 20K cut resistant socks

[1] Reebok International Ltd., Massachusetts, United States.

6.2.5.2 MOD issue tropical desert tan socks

The tropical desert tan socks are issued to all services of the MOD. They are dual tone beige and white and ribbed for use in warm and hot climates. The socks are treated during manufacture with a permanent silver ion finish to give them anti – microbial properties.

Composition: 73% polyester micro – fibre, 12% cotton, 10% nylon and 5% elastane.

Figure 6.2: MOD issue tropical desert tan socks

6.3 Preliminary test setup and method

30g of N160 propellant was weighed into the case which was then loaded with 50g of sand. Wadding was then added to the top and tamped down and the case was sealed on the top. The steel cylindrical case was fired using a 30mm barrel 1135 mm. The target for these sets of trials was a gelatine surrogate that was protected by either the sole of a Dunlop Wellington Boot (DWB) or a combination of the sole and different types of socks that were fitted onto the surrogate leg (table 6.1).

Table 6.1: Test variable for gun based tests with respect to different socks

Distance (mm)	500
Case	Steel cylindrical case
Propellant weight (g)	30
Targets	All of the trials were conducted using a gelatine surrogate: Reebok 20K cut resistant skate socks (RBK), MOD issue tropical desert tan socks (STD), two layers Reebok 20K cut resistant skate socks (2xRBK), Dunlop Wellington boot sole (Sole)
Sand (g)	50

The impact events were recorded using a Phantom high – speed video camera (V12) (10000 fps, 6µs exposure time and 1280 x 480 resolution) and illuminated using two 2kW halogen lights. From the high speed video, a record was also made in regards to the shape of the sand, whether it was a slug or not. Post – tests the depth of penetration of sand for each of the trials was recorded.

6.4 Results and discussion

The results of the trials on the effect afforded by socks to gelatine legs is given in table 6.2.

Table 6.2: Gun based test results of the effect of protection offered by socks to gelatine legs

Trial no.	Propellant (g)	Distance (mm)	Target	Velocity (m/s)	Penetration (Yes/No)	Slug (Yes/No)	Penetration depth (mm)
1	30	500	Sole	909.1	Yes	Yes	182
2	30	500	Sole	885.6	Yes	Yes	180
3	30	500	MOD	963.6	Yes	Yes	152
4	30	500	MOD	950.6	Yes	Yes	148
5	30	500	RBK	953.4	Yes	Yes	120
6	30	500	RBK	928.1	Yes	Yes	125
7	30	500	2xRBK	969.9	Yes	Yes	97
8	30	500	2xRBK	942.6	Yes	Yes	95

In all of the cases the heel was completely destroyed; however, as can be seen from the data the double layer of Reebok Kevlar offered the best protection in terms of the least depth of penetration. The results also show that the method developed in the previous chapter is able to produce consistent results with consistent velocities (mean = 934.0m/s, s.d. = 26.9m/s) and slugs produced.

As can be seen from the below images of the trials against a gelatine leg with a Dunlop Wellington boot sole attached but without a sock the damage is much more severe with the entire leg being split along the axis with a higher average depth of penetration of 181mm, which was true for both of the trials (figure 6.3).

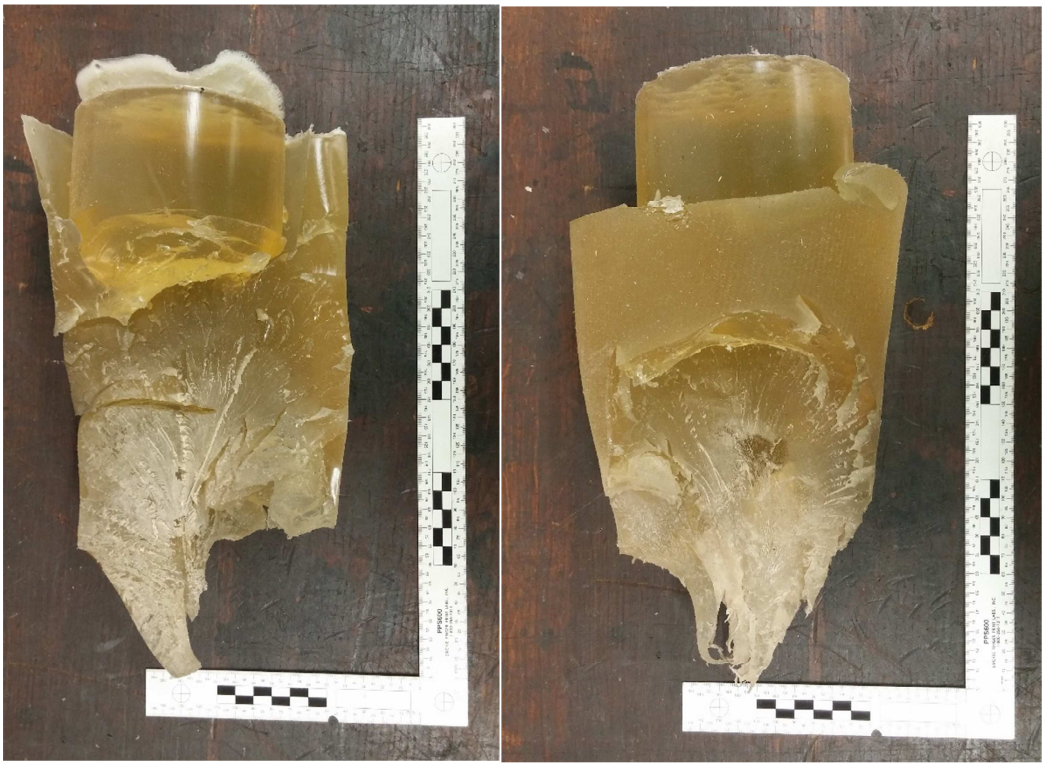


Figure 6.3: Gelatine leg with sole on, without sock; Trial 1 on the left, Trial 2 on the right; result of gun based tests looking at the effect of socks

Below are the images of the trials conducted using the MOD issue socks (figure 6.4). Immediately it can be seen that there is a difference in the outcome. As expected the heel was completely destroyed, but surprisingly more of the tissue above the ankle remained intact; which was confirmed by a lower depth of penetration which had an average of 150mm which is 30mm lower than when a sock was not used. This was unexpected as it was assumed that the socks would not be able to offer any form of protection. Visual examination of the socks post trial reveals that the socks have been torn along their seams, which might explain the protection offered by them. The socks offer initial protection against the abrasion effects of the sand and other debris produced by the destruction of the sole. This protection afforded by the sock is only up to a certain threshold after which the socks breakdown, tearing along the seams at the ankle letting the rest of the debris into the leg. This however, offers sufficient initial protection to show a difference when compared with trials where no sock was used.

Figure 6.4: Gelatine leg with sole on, with MOD issue sock; Trial 3 on the left, Trial 4 on the right; result of gun based tests looking at the effect of socks

Below are the images of the trials conducted using the Reebok 20K cut resistant socks (figure 6.5), immediately it can be seen that there is a difference in the outcome between these and the MOD issue socks. As expected the heel was completely destroyed, and since the sock has Dyneema™ woven into the socks above the ankle it offers better protection than the MOD issue sock which can be seen in the depth of penetration numbers which was an average of 122.5mm which is on average lower than those seen when using the MOD issue sock. As was seen in the previous trials using the MOD issue socks, the socks offer initial protection against the abrasion effects of the sand after which the socks suffer tears along the seams providing a path for the debris into the leg. The threshold in this case is higher than that afforded by the MOD issue sock which was expected due to the Dyneema™ in the sock. As previously observed failure occurs along the seams at the ankle where there is usually a transition between different materials; which in this case appears to be between cotton and Dyneema™.

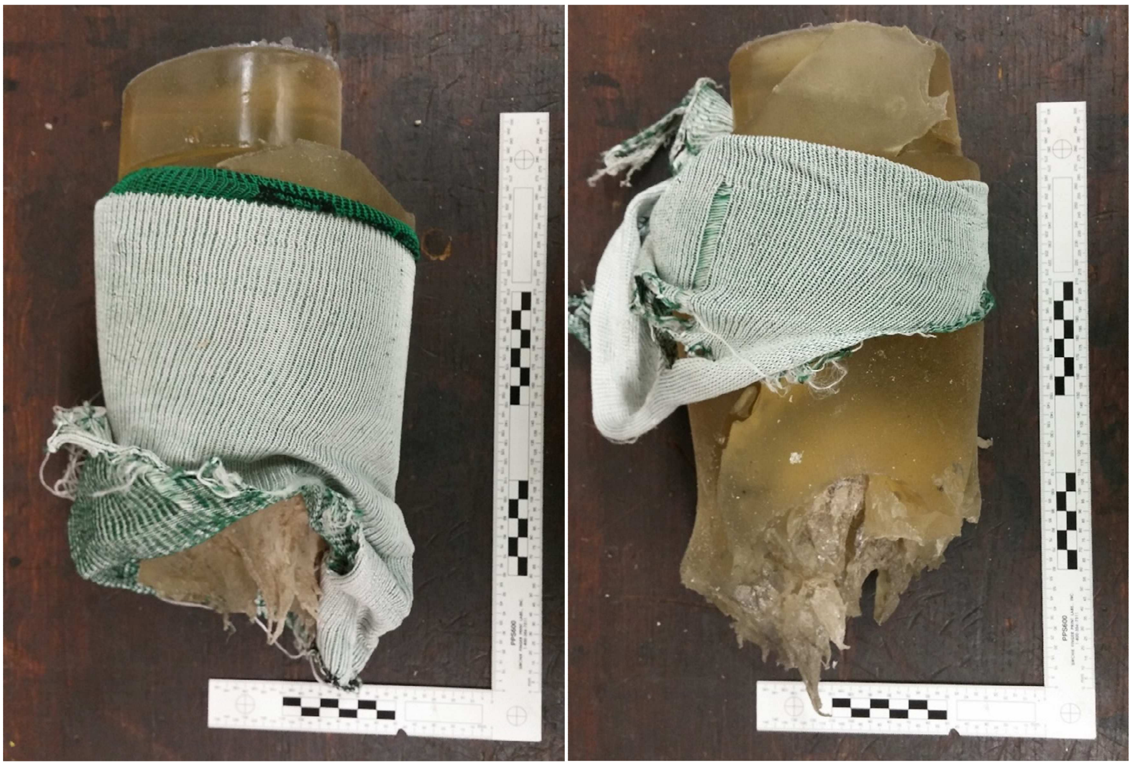


Figure 6.5: Gelatine leg with sole on, with Reebok 20K cut resistant sock; Trial 5 on the left, Trial 6 on the right; result of gun based tests looking at the effect of socks

The images below are of the final trials using two of the Reebok 20K cut resistant socks on each gelatine leg (figure 6.6). Similar to the previous trials everything below the ankle was completely destroyed. The purpose of these trials was to see if increasing the number of layers increases the protection afforded, and as can be seen from the depth of penetration data and the images, this appears to be the case which had an average depth of penetration of 96mm which is lower than all the previous scenarios. Failure occurs along the seams at the ankle where there is a transition between the different fabrics (Cotton and Dyneema™). However, the data suggests that the double layer of socks offers a higher threshold before which the failure occurs to the environmental debris.

Figure 6.6: Gelatine leg with sole on, with two Reebok 20K cut resistant socks; Trial 7 on the left, Trial 8 on the right; result of gun based tests looking at the effect of socks

From all of these trials it can be concluded that socks do offer a certain degree of protection from the penetration from the environmental debris up to a certain threshold. Just adding a MOD issue sock can decrease the penetration depth by up to 30mm compared to having no sock. It appears that this threshold can be further increased by:

- Using socks with more robust materials
- Using multiple layers of the same sock

From the trials it can be seen that failure occurs along the seams that are present along the ankle and heel where there is a transition between different materials. Hence, it might be possible to increase the threshold before which failure occurs by moving the seam above the ankle thereby having a continuous material at the foot thereby reducing failure points. It was also observed from the trials that once the seam was destroyed it would result in the socks peeling from the leg during the blast due to its elastic nature. Hence, it might be possible to reduce the ingress of contaminants due to this by devising a fastening mechanism along the ankle, whether this be incorporated into the socks itself or a separate item. However, this is not part of the scope of this PhD and will have to be reserved for future work to be done.

Chapter 7: DISCUSSION

Humanitarian deminers and military personnel are under constant threat of the dangers of land mines when they are deployed in zones where mines have been widely proliferated. While anti – personnel mine boots have been designed specifically for this purpose, they are quite limited both in their performance and ergonomics, to be worn continuously. This has highlighted the issue of whether it is possible to achieve a certain degree of performance from commercially available products like boots and socks that provide a manageable surgical outcome.

Early work conducted by Fujinaka et al. (1966) demonstrated that commercial boots are not effective in providing adequate protection against a land mine and would result in amputation. This was further confirmed by the work by Lans (1999), Harris et al. (2000), Bergeron et al. (2006), Van der Horst et al. (2008) and Nicol (2011) where none of the commercial boots provided protection and in most cases even anti – personnel mine boots were not able to afford adequate protection against a small mine. The inconsistent results from the limited studies in open literature with respect to blast testing combined with requests from industry to develop a method to test boots against mines, set the way for this current research. An initial investigation into the performance of commercially available boots using blast testing confirmed this. It also highlighted issues that were observed in the literature with respect to the reliability and reproducibility of the result, where small changes in the parameters would affect the results considerably. Testing showed that none of the boots tested offered adequate protection against a 20g PE4 charge with loads exceeding the fracture threshold of the lower limb. It was found that moisture content of the soil affects the results when all other parameters are kept constant and that the construction of the boots has an effect on the loads measured and the level of contamination which matches the observations made by Nicol (2011).

The blast tests are time consuming and expensive to conduct putting a large restriction on the number of trials that could be performed. This combined with the issue of reliability and reproducibility necessitated the development of a new test methodology. This led to the development of the gun based test which went through a number of iterations from using sand loaded into sabots to a custom designed shell that contained the required quantity of sand. Fujinaka et al. (1966) stated that the two important factors that determine the protection offered by the boot is the total impulse and the impulse per unit area values. Hence, the gun based test was designed to match the total impulse and impulse per unit area output of the blast test. Statistical analysis of the gun based tests using 160mm sabots showed that the formation of the slug had a significant effect on the loads and velocities measured. This meant that in order to achieve penetration of the boots being tested it was necessary for the sand to exit in the form of a slug, forming a sand cloud having a defined sand cloud shape in the form of a cone. Testing of the gun based system demonstrated that by using the sabots it was possible to generate enough impulse per unit area from the sand cloud to cause penetration, but this is entirely dependent on whether a slug was formed. To eliminate the inconsistency related to the formation of the slug, testing was moved towards using the design of a hollow cylindrical steel case which was capable of producing an impulse per unit area value higher than the blast test. This led to the production of repeatable and reproducible results where the loads and velocities recorded were consistent with the impulse per unit area matching that of the blast test.

7.1 Effect of the burial depth, standoff distance and the moisture content of the sand.

Hlady, based on the work done on studying the effect of burial depths on loads measured, states that there is an optimum burial depth for each charge weight (Hlady, 2004). If the burial depth was non – existent or too small, it would result in the energy from the blast dissipating into the air resulting in lower loads measured. Additionally, if the burial depth was too large, a large portion of the energy would be absorbed by the surrounding soil in addition to a portion used up to move the soil, hence resulting in lower loads. Since for the blast tests the burial depth was fixed at 60mm based on the observations made by Nicol (2011), it was not possible to compare this with the observations made by Hlady (2004). However, the same principle should be applicable to gun based trials when looking at the effect of sabot lengths on the velocities recorded in table 7.1.

Table 7.1: Effect of sabot length on the velocities recorded in gun based testing

Sabot length (mm)	Weight of sand (g)	Velocity (m/s)	
		White paper	Brown paper
100	114	Not recorded	341.3
120	135	439.4	Not recoded
140	160	360.2	351.0
160	178	609.1	619.7
180	205	439.4	306.8
200	228	492.5	416.8

In gun based tests there is not a burial depth but rather a certain weight of sand that is sitting in front of the propellant, the height of which varies depending on the weight of the sand since only the height of the sabot changes with weight. As can be seen from table 7.1, for the same propellant weight of 40g N160, the velocity of the sand cloud varies as the length of the sabot changes. This can be explained by the internal ballistics of the test where there is an optimal rate at which the gases expand when the propellant burns. When the weight of the projectile is too low, the projectile starts moving before the propellant has burned completely. Due to this a lower backpressure is developed by the time the projectile moves, resulting in lower velocities and lower energy of the projectile. When the projectile is too heavy, the propellant burns completely but the fall – off of the pressure is more rapid, since more energy is required to move the projectile, leading to a lower velocity and lower energy. Hence, there is an optimum projectile weight for each propellant weight depending on the length of the barrel and the dimensions of the chamber that is governed by the laws of internal ballistics (AMCP, 1965). As can be seen from table 7.1, up to 160mm sabot length as the length of the sabot increased the velocity increased. This is because at the lower lengths the weight of the sand in front of the propellant was not sufficient enough to develop sufficient back pressure during the ignition in addition to which the lower weight of sand meant that it would exit the barrel before the propellant had undergone complete combustion resulting in unburnt propellant all of which resulted in lower velocities of the sand cloud. For paper sabots above 160mm the velocity was lower since the increased weight of the sand meant that the backpressure used to move the sand cloud through the barrel diminished more rapidly than when a lower weight of sand was used which meant that the sand cloud would exit the barrel at a lower velocity. This shows that like burial depth in blast tests, weight of the sand plays a factor in gun based tests in determining the loads measured, which is comparable to the observations made by Hlady (2004).

The literature (Muschek et al, 1997; Mah et al, 2007) identifies that increasing the standoff distance decreases the loads transferred. Although this observation was made with respect to blast tests, it can be applied to the gun based tests as well. This can be observed in the results of the 160mm paper sabots at different distances from the plate (table 7.2).

Table 7.2: Effect of distance on load measured in gun based tests

Propellant weight (g)	Distance (mm)	Target	Peak load (kN)
40	600	Plate	119.4
40	500	Plate	173.6
40	400	Plate	201.8

As shown in table 7.2 above, for the same propellant weight of 40g N160 against the same target, the loads decrease as the distance from the target increases. This is because as the distance increases the velocity of the sand cloud decreases, and the sand cloud expands even more at longer distances which mean that a larger portion of the sand misses the target as the distance increases. This means that the sand cloud has less energy as the distance increases and therefore transfers lesser energy to the plate resulting in lower loads measured.

The above was when the standoff gap was air. When the standoff gap is made up of another material the same result can be seen. This was seen while testing different thickness of foams in the form of different number of layers of the same foam for the same velocities. It can be seen in chapter 3 that when the thickness of the foam was increased, for the same velocity the loads measured would decrease. This is because the energy of the impact would be absorbed by the collapsing of the foam cells. And since the cells were already collapsed they would require less energy to do so again in subsequent impacts which is reflected by the higher loads when using pre – crushed foams. While the foams can reduce the peak impact force, it was observed that foams were not able to lower the percentage of the load that was transferred from the striker to the anvil. This means that the foams cannot completely remove the impact force, since it can only absorb a fraction of the impact energy by crushing the cells resulting in 90% of the load of the striker measured at the anvil. Based on the data from the foam testing, the thickness of foam that would be required to reduce the loads measured from a 20g PE4 was 80mm which increases to 320mm for the gun based testing using the steel casing.

The results of the blast test demonstrated that the moisture content of the soil has an effect on the loads measured. This agrees with the work done by Hlady (2004) that quotes an increase of 500% in loads measured when the moisture content of the soil is increased from 6% to 20% at a burial depth of 50mm for a 25g charge. Similar increases in the loads was observed in blast tests when the moisture content was changed from dry sand to moist sand with 5% moisture content.

Table 7.3: Effect of soil moisture on loads measured

Charge weight (g)	Burial depth (mm)	Soil condition	Peak force (kN)
20	60	Dry	96.3
20	60	5% moisture	125.7

From the above table (table 7.3), although no repeats were performed, for the same charge weight and the burial depth, the peak loads measured increased as the moisture content increased from 0% to 5%. This is an increase of approximately 130% for a small increase in moisture content which lines up with the observations made by Hlady (2004).

7.2 Validation of the gun based tests against blast tests

In chapter 5, the total impulse, impulse per unit are, energy and energy per unit area were calculated for the blast test. The same calculations were performed in chapter 5 for the gun based tests which makes it possible to compare these two types of tests. The results of the calculations as seen in chapter 5 are as follows:

Since the total impulse result for the blast test depended on the method used to calculate them, it varied widely. The total impulse varies from 110 – 196N.s depending on the test used, resulting in the impulse per unit area varying from 5073 – 8925N.s/m^2. The methods used to calculate these values such as the Tremblay (1998) equation are based on a mine that is offset from the target and is validated when there is a standoff distance, while the high speed video has the sand completely obscuring everything after a very short time period. Hence, these values are only estimates that give an approximate measurement which allows it to be compared to the gun based test. The total impulse and impulse per unit area calculations of the gun based tests shows that the steel cylindrical case has a lower total impulse (47.8N.s) compared to the blast test (196.4N.s), but since it acts over a smaller area its impulse per unit (9556N.s/m^2) area exceed that of the blast test (8925.5N.s/m^2). This means that the two tests are comparable in terms of the impulse per unit area since gun based test exceed the blast test by approximately 7%. When looking at the energy and the energy per unit area values of the two tests, the gun based test (4565.8KJ/m^2) exceeds those of the blast test (289.1KJ/m^2) every time due to the smaller amount of sand that is moved at much higher velocities. This lines up with the work done by Fujinaka et al. (1966) that states that the impulse per unit area is one of the important factors that determine protection offered by the boot with the other factor being total impulse.

While it is good that the impulse per unit area values for the two tests are close to each other (gun based test – 9556N.s/m^2, blast test – 8925N.s/m^2), it would be useless if the gun based test was not able to replicate the force – time curve of the blast test. Here Dunlop Wellington boots (figure 7.1) from gun based testing are compared to Lowa desert elite's (figure 7.2) from blast testing since they were not used in both tests making comparison between each test for a particular boot impossible.

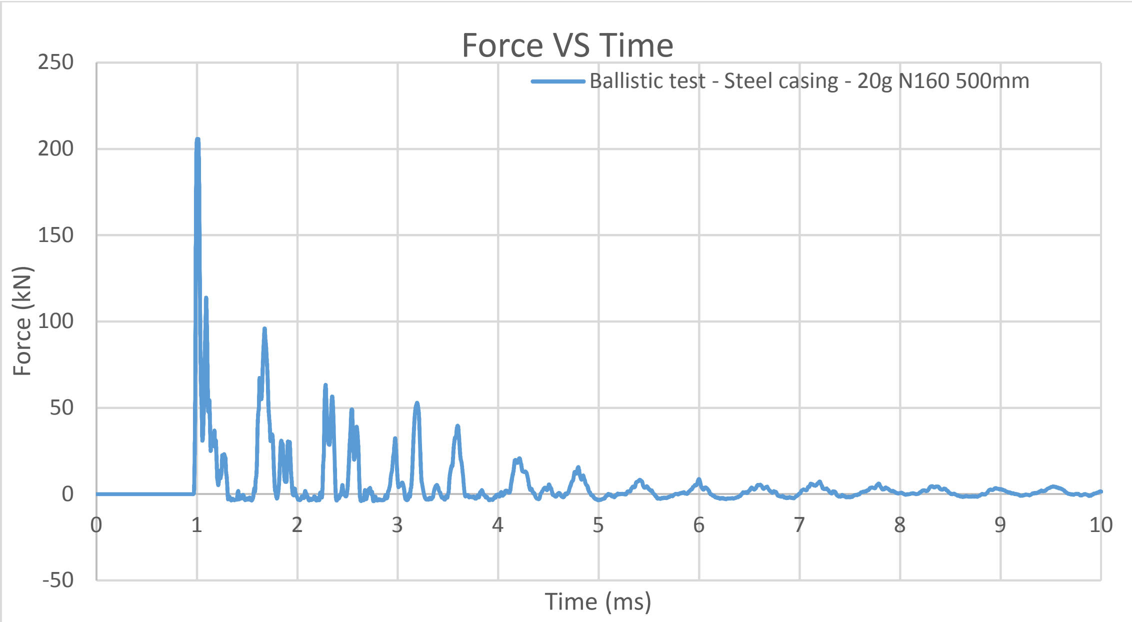


Figure 7.1: Force – time curve for Dunlop Wellington boots in gun based tests using steel cylindrical case

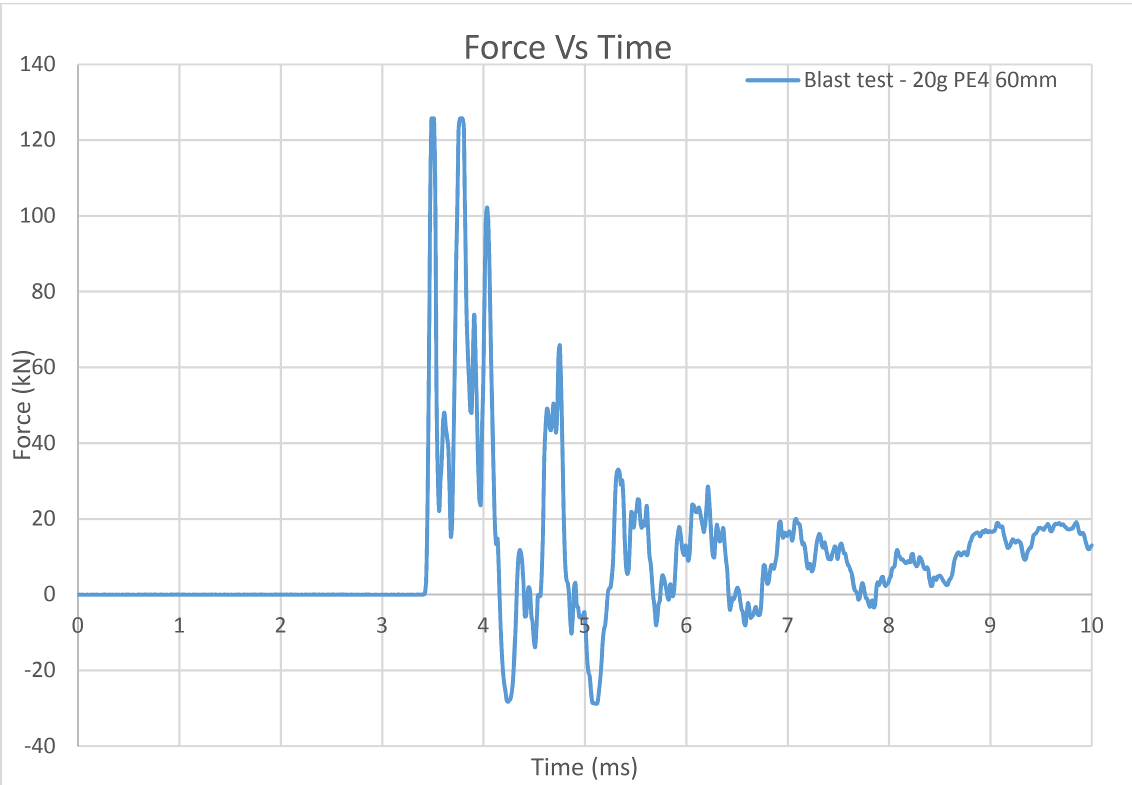


Figure 7.2: Force – time curve for LDE in blast test

Figure 7.1 and figure 7.2 shows that the force time curve for both the tests have multiple peaks due to the reflection of shock wave within the metal rig. The gun based tests are able to produce greater loads than the blast tests while having a similar duration of the initial force peak (approximately 0.3ms). All of this demonstrates that the gun based test is a good replacement for blast testing.

7.3 Reliability of blast tests compared with gun based tests

As the literature shows a large number of blast trials have been conducted to assess the performance of different types of boots whether they are commercial ones (Lans, 1999; Van der Horst et al, 2008; Mah et al, 2007; Nicol 2011) issued for general use or mine resistant boot designed particularly to deal with land mines (Lans, 1999; Harris et al, 2000; Bergeron et al, 2006; Nicol 2011). One of the biggest problems with blast tests is comparing results when the variables are different between the different studies. Also, blast testing tends to have poor repeatability due to the number and type of variables and the poorly controlled environment. Changes in the humidity, position of the fuse within the charge, the packing of the soil and small differences in the position of the mine can produce different results where it is often difficult or impossible to control them. This can be observed in all the research conducted that is cited in the literature review. The same was true for the blast (table 7.4) testing that was conducted using gelatine surrogate in this chapter 4.

Table 7.4: Blast test results at 60mm depth using gelatine legs showing differences in output for the same variables

Boot used	Soil condition	Peak force (kN)	Total impulse (N.s)	Sand velocity (m/s)
DWB	Dry	63.7	215.4	67.8
DWB	Dry	47.3	194.8	43.9
DWB	Dry	64.9	333.3	77.6
LDE	Dry	38.0	191.5	70.2
LDE	Dry	25.6	235.7	66.1
LDE	Dry	26.9	157.2	51.8

Table 7.5: Blast test results showing the effect of moisture content with respect to loads measured

Boot used	Soil condition	Peak force (kN)	Damage level	Sand velocity (m/s)
ALT	Dry	96.3	BD3	65.5
ALT	Wet	125.7	BD3	62.1
LDE	Dry	125.7	BD1	59.5
LDE	Wet	113.1	BD3	53.5

The literature (Hlady, 2004) shows that the moisture content of the soil plays a role in the loads measured and this can be seen in the case of the Altberg MKII boots (table 7.5). However, the same was not true for loads measured for the Lowa desert elite boots for dry and wet soil (5% moisture), where the dry soil produces higher loads than the wet soil despite the fact that the boot fails in the trial using the wet soil. This indicates that something might have changed during that particular trial, which highlight the unreliability of blast testing. This combined with the fact that blast testing is generally quite expensive and time consuming makes it necessary to have an alternate more reliable means of testing.

This is where the gun based testing comes in, where the validation tests show that it was possible to replicate the results of the blast test consistently with a high degree of accuracy and repeatability. Moreover, it is possible to target specific velocities of the sand cloud by altering the propellant weight and the weight of the sand to replicate different degrees of damage. This is not to say that gun based testing is completely free of the issues that plague blast testing, where similar to the blast test the velocity of the sand cloud can vary depending on the humidity, ambient temperature and whether the propellant has undergone complete combustion. However, in gun based testing since these are conducted indoors, it is easier to control them. On average, the setup time for each of the blast test was longer than that for the gun based test which meant that it was only possible to conduct 6 – 8 tests over a two – day period compared to 25 – 30 trials of the gun based test over the same period. This combined with the relatively cheaper cost of the gun based test with their ability to produce more repeatable results makes it a better alternative to blast testing and would enable comparison between different research.

7.4 Evaluation of 20% gelatine as a surrogate leg and comparison vs metal surrogate. Understanding boot damage criteria with respect to the loads measured.

Different types of surrogates have been used in the literature (Bergeron et al, 2006; Van der Horst et al, 2008; Mah et al, 2007) from metal surrogates to more complex hybrid surrogates such as the Canadian lower leg (CLL) or the Frangible surrogate leg (FSL) which uses a tissue substitute to simulate human tissue and a bone substitute to simulate human bone. Both of them have their advantages and disadvantages, with respect to ease of production, cost, reusability and reproducibility.

The metal surrogates are typically easier to produce and are cheaper, allowing them to be used consistently to produce reproducible results. However, they are quite limited in their ability to study tissue damage, since they usually are comprised of pieces of metal that have been attached together to roughly simulate a human foot and leg. They lack the complicated structures present in a human foot, hence making anything other than base observations impossible and makes it necessary to use measurements of load. However, the cost and their ease of production make them attractive, particularly when tissue and bone damage is not a factor and when priority is being paid to the damage to the boots.

On the other hand, while the hybrid legs provide the necessary structures with it to make more nuanced observations about medical outcomes such as fractures and contamination possible, they become quite limiting when their cost is considered. When metal surrogate was used the measurements made as part of the trial was the loads which were produced by the blast. The robustness of the surrogate was such that it made it possible to use the same surrogate multiple times till failure occurred in the surrogate. On the other hand, the hybrid legs are not designed for this purpose. They have been typically designed to study the loads and tissue damages as part of car crashes and accidents. The loads produced in the blast tests were so high that if these hybrid legs were used as the surrogates it would have resulted in catastrophic failure every time which would mean having to obtain a new surrogate for every repeat, which together with the cost of the leg would make the total cost of the experimental trial unfeasible. Hence, to overcome the costs associated with such trials it was decided to use two different systems, one to study the load and the other to study the effects of contamination.

From the literature (Bergeron et al, 2006; Van der Horst et al, 2008; Mah et al, 2007) it can be observed that the loads measured vary quite significantly between the different studies. It has to be kept in mind that this was due to the large number of variables involved. However, it can also be observed that in some studies the surrogates used were different, leading to different loads measured making comparison between the different studies difficult.

In the current work, loads were measured for the blast test using both a metal surrogate and a 20% gelatine surrogate. It was immediately obvious that the loads measured depend heavily on the surrogate used. The loads measured using the metal surrogate were usually 4 – 6 times the loads measured by the gelatine leg in the blast test. This was because compared to the metal surrogate the gelatine surrogate allows for a certain degree of compression. From the high speed video, it appears that the gelatine leg undergoes a certain degree of vertical compression which results in horizontal expansion to compensate for it. This was one of the reasons why the blast tests using the gelatine surrogate and different boots resulted in catastrophic failure of the boots. The horizontal expansion more than likely exceeded the tensile limit of the boot upper resulting in it bursting.

Now if the gun based tests are considered, the loads measured by the gelatine surrogate are much lower than those of the blast tests. This was because while the blast tests are a vertical test, the gun based test is a horizontal one. Hence, while the same phenomenon of compression and expansion occurs, the foot undergoes catastrophic damage to the heel and the attachment of the gelatine surrogate to the leg is already destroyed before the majority of the load has been transferred to the load cell. This was not an issue however, since the load measurements for the blast and the gun based tests using the metal surrogate shows that loads are quite close to the limit of the load cell in both of the cases. In addition, the impulse per unit area measurement also shows that in both types of tests the gelatine surrogates are subjected to similar stresses, and hence the damage levels should be comparable.

The load data confirms that boot damage alone is not enough to be used as a predictor for foot or leg injuries. In the blast test and gun based tests while a few of the boots showed very little superficial damage, if they alone were used as an indicator it would mean that the leg was relatively protected. However, the load data tells an entirely different story, where the loads were several times the lower limb fracture threshold, which would have resulted in many fractures of the foot, heel, ankle and other bones of the leg. However, the method developed by Bass et al. (2004) called the boot damage criteria to assess the performance of boots was based on using Hybrid 3 legs as a surrogate which are inherently solid allowing for a good transfer of the loads to the load cell. In the case of gelatine surrogates this is not possible as explained above and loads measured are significantly smaller despite being able to penetrate the boots which would result in an overestimation of the performance of the boots. Hence, it is necessary to consider the surrogate used while using the boot damage criteria to assess the performance.

Due to the fact that the gelatine leg is a homogenous structure that lacks the structural details of a cadaveric human or animal leg, it was not possible to make a medical assessment of the damage. A solution would be to determine the energy transferred to the leg based on the number of fissures and the length of each of them. However, it became obvious immediately that this would not be possible due to the nature of both the blast and gun based testing where the ankle was completely destroyed, in addition to large portions of the gelatine surrogate missing. As a result, it was decided to take the depth of penetration measurements and use them as a measure of the protection offered by the boots. Hence, the lower the penetration, the better the performance.

In a situation where it might be necessary to obtain both the loads and a medical analysis of the damage to the surrogate it might be possible to use the gelatine surrogate to encase a much thinner metal surrogate or another surrogate that has bio – mechanical properties similar to that of human leg. This would allow for more accurate load measurements than would have been observed similar to the literature if hybrid surrogates or cadaveric limbs were used. However, for this PhD, this was decided against since the primary focus was to develop a gun based test that could simulate the blast test, and fabricating metal surrogates or procuring surrogates with bio – mechanical properties similar to that of a human leg would be cost prohibitive, since it was likely that they would be destroyed during each trial. Moreover, from the gun based test it was observed that the fissure path through the gelatine surrogate mostly followed the axis of heel since that was targeted to simulate the heel being the initial point of contact with the mine, hence incorporating a surrogate into the gelatine would introduce an obstacle around which the sand would have to move making depth of penetration in the best case scenario inaccurate or in the worst case impossible. Additionally, this would not allow for more detailed medical observations to be made, unless more complex structures were incorporated which would significantly increase cost.

All of this shows that it is not possible to protect the foot even against a small charge resulting in the ankle being completely destroyed when commercial boots are used. These boots are not designed for this purpose, and therefore were not expected to provide the required level of protection. However, since they are widely used by current military personnel it made it an ideal range of product to test. This testing demonstrates that if there is information already available on hand about the risk of potential mines in the near vicinity, then it is imperative to wear the correct personnel protective equipment to deal with it. However, as the literature (Muschek et al, 1997; Harris et al, 2000; Bergeron et al, 2006; Nicol 2011) shows even these are only able to offer a certain degree of protection even against small mines and even then it would result in significant damage to the ankle and below. In addition, contamination of the soft tissue is guaranteed and the degree depends on the nature of the mine, the surrounding environmental debris and the level of protection worn.

7.5 Effect of boot construction and socks on contamination

Of all the boots (Lowa Desert Elite, Altberg MKII and Standard British Combat Boot/Assault Boot) tested as part of the blast and the gun based test in addition to the Dunlop Wellington boots used, the Lowa desert elite's performed the best. The following are the cross sections of the three different boots used (figure 7.3, figure 7.4 and figure 7.5).

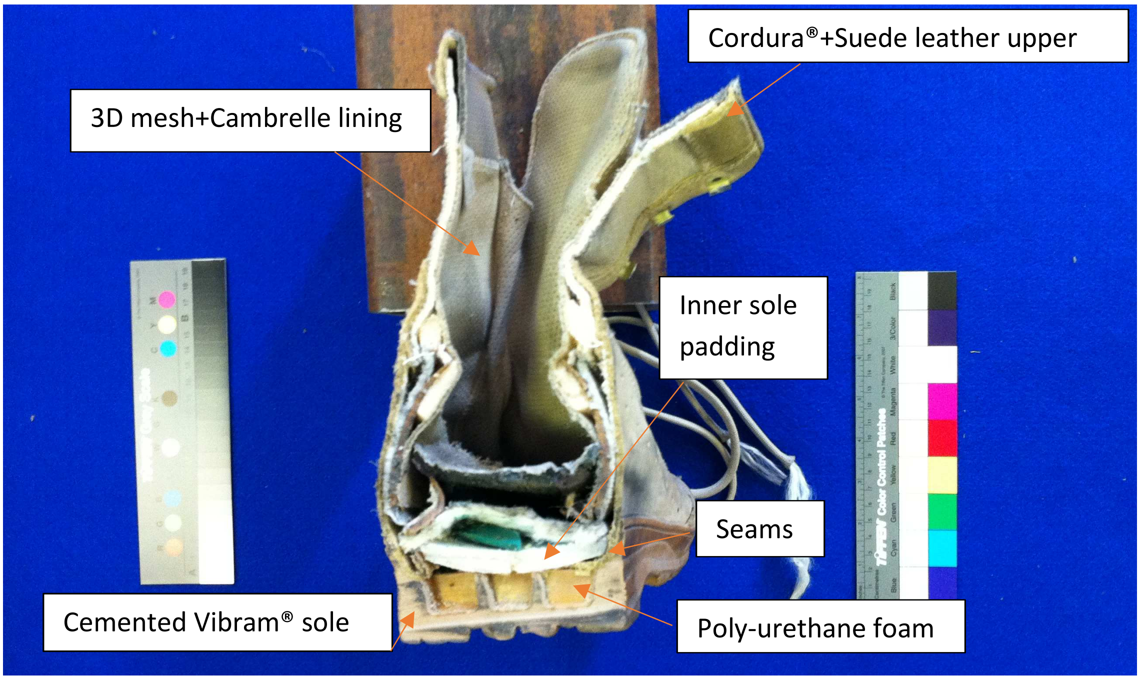


Figure 7.3: Cross section of Lowa desert elite (LDE)

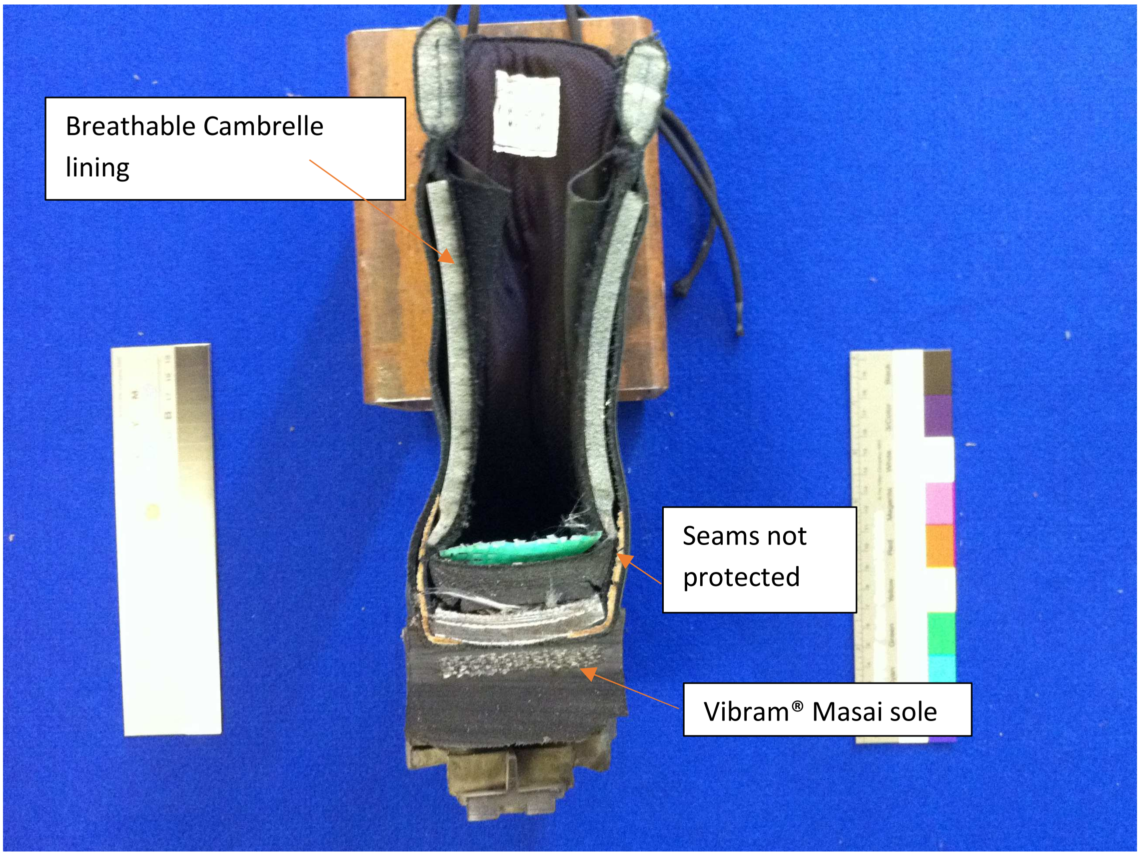


Figure 7.4: Cross Section of Altberg MKII (ALT)

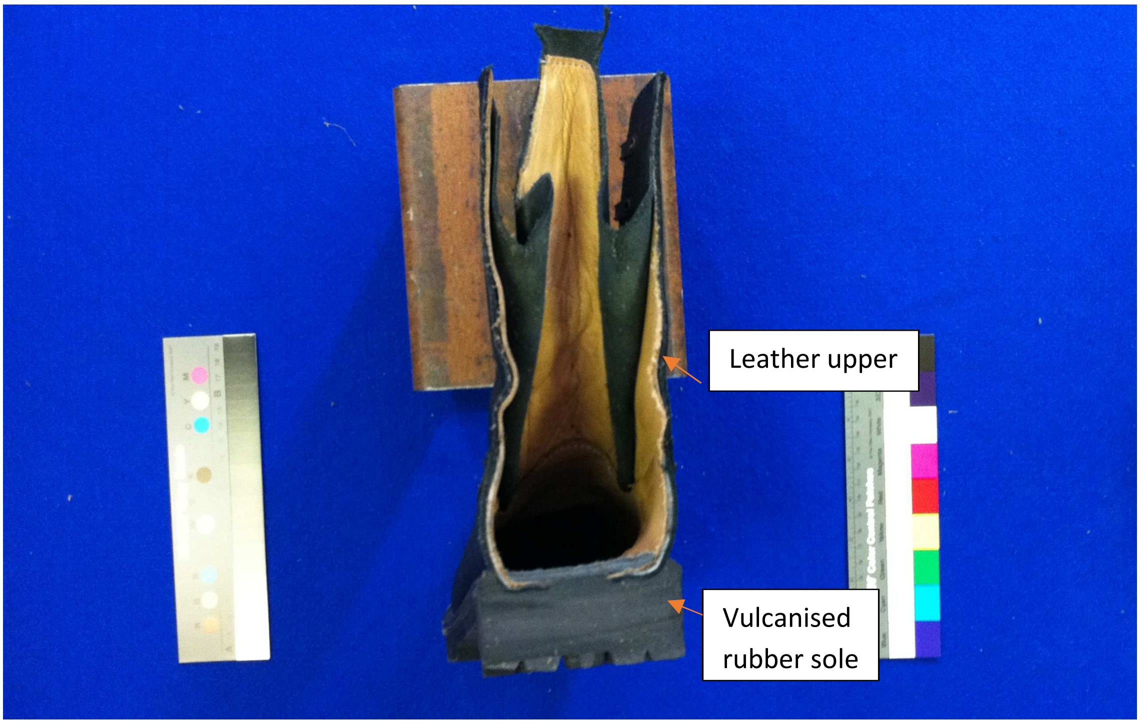


Figure 7.5: Cross section of British combat boot/assault boot (BCB)

The above are cross sectional images of the Lowa desert elite (figure 7.3), Altberg MKII (figure 7.4) and British combat boot/assault boot (figure 7.5). The blast and the gun based tests demonstrated that the Lowa desert elite boots generally performed better than the rest. A visual examination of the cross sectional area of the boot reveals that it has a more complex sole construction when compared to the other two. Primarily the sole is not a single piece of foam or rubber but rather consists of compartments that contain the rubber from which the sole is made (Vibram® MSV) that is enclosed in the same material from which the upper is made. This means that the upper is embedded much deeper into the sole, which grants it additional protection and stiffness. In addition, the sole extends a bit into the upper granting protection to the seams where the upper is cemented into the sole. The other boots consist of a single piece of polymer (rubber or foam) onto which the sole is cemented without any additional protection for the seams. In the Lowa desert elite and the Altberg MKII the inner sole is lined with similar material from which the upper is made although the Altberg MKII has additional padding in the upper, but both have padding in the sole in the form of foam to afford additional comfort. Both of them additionally have a plastic foot shaped layer the purpose of which is not known. All of this contributes to the higher cost of the two boots which is in contrast to the British combat boot which is the cheapest of the three and only consists of a single piece of polymer as the sole onto which the upper has been cemented. As a result of this the British combat boot offers the least amount of protection against both the blast and the gun based test. The far more superior construction of the sole in the case of the Lowa desert elite and the harder sole appears to be the reason why it performs better than the other two. This lines up with some of the observations made by Nicol (2011) regarding the construction of the boot playing a role in the performance of the boot against a land mine. It appears that if fewer areas that have a higher chance of failure due to presence of seams or higher stresses due to transition between two different materials are exposed to blast waves, the better the chance the boot has of surviving. This can be seen in the case of Lowa desert elite. However, care has to be taken regarding this assumption since all of these tests were undertaken against small charges which are relatively small by blast mine standards.

Based on the hardness of the foams in the soles used in the blast and gun based testing, foams of different densities that match this hardness were tested. Impact testing of the foams revealed that for a particular velocity increasing the foam thickness decreases the loads measured but increases the total impulse, demonstrating that while foams can reduce the loads to a certain degree by increasing the thickness it might result in significantly more damage by increasing the duration of the force. This lines up with the observations made by Fujinaka et al. (1966) that it is not the loads that are the primary mechanism of damage but the total impulse and impulse per unit area.

However, if the boots are penetrated the results show that the sand debris goes quite far up the leg. The testing of different types of socks has shown that it is possible to reduce the degree of penetration depending on the materials used in the construction of the sock thereby limiting how far up the leg the debris travels. In tests without socks, when the sand cloud acts on the boot a portion of the energy is used to penetrate the boot and beyond that most of the energy of the sand is spent travelling up the leg. When a sock is used, it introduces further barriers through which the sand has to penetrate which means that more energy of the sand cloud is used doing that. This is shown in the testing, where surprisingly socks issued as part of the kit to the British Army are able to reduce the depth of penetration of sand when compared to tests where no socks are used. This means that it might be possible to reduce the depth of penetration of environmental debris to sufficiently low levels, thereby improving the medical outcome by just using socks that have the desired properties. Now if the Reebok 20K skate socks that have Dyneema® in them are considered, it becomes obvious that the failure point is along the seams where the socks transition from cotton for the foot up to the ankles to Dyneema® for the ankle and above. Since the failure occurs at the ankle seams and the worst case scenario is someone stepping on a mine with their heel, the ankle would be the location that would require the most reinforcement. Moreover, as the pictures in the previous chapter demonstrate, after the socks fail at the ankle they are peeled away from the leg offering no more protection. Hence, a good idea would be to offer additional reinforcement above and below the ankle all around the leg in the form of a band that would prevent the sock from peeling and hopefully increasing the protection offered. A similar effect might also be achieved by incorporating the same type of protection into the boot itself in addition to the socks which would increase the overall level of protection for the foot. This can be seen in the tests where by just increasing the number of layers of the socks, it is possible to reduce the depth of penetration by approximately 25%. Since only two repeats were performed for each sock this requires further testing. However, looking at all the sock testing as a whole, it demonstrates that socks do play a positive role in reducing the contamination effects of blast thereby improving the surgical outcome.

Chapter 8: CONCLUSIONS AND SUGGESTED FURTHER WORK

This chapter will summarise the entire work that was undertaken into a number of conclusions while providing suggestions for further work based on issues not tackled.

8.1 Conclusions

The following conclusion can be drawn from this work

1. Blast testing is unreliable due to the large number of variables involved making it difficult to obtain reliable and reproducible results. Blast testing inherently produces varying results when all the variables have been kept the same just because of their volatile nature. Changes in the humidity, position of the fuse within the charge, the packing of the soil and small differences in the position of the mine can produce different results where it is often difficult or impossible to control them. Changes in the moisture content of the soil and burial depth significantly effects the loads measured.
2. Most of the commercial boots tested do not offer adequate protection against even a 20g charge of PE4 at 60mm depth. While the Lowa desert elite boot fared better than the other boots visually, the loads measured still exceeded the lower limb fracture threshold by a significant margin. Boot construction does affect the survivability of the boots, with fewer areas exposed that have a higher chance of failure the better the chance of survival as seen in the case of Lowa desert elite’s.
3. Gun based testing is reliable and is able to meet the performance of blast testing with respect to the loads measured and the impulse per unit area. It is able to produce consistent velocities and can be easily altered to meet desired velocities by changing the propellant weight and sand weight. It was found that the formation of a sand slug had a significant effect on whether penetration occurred and the measured loads and velocities. The standoff distance and the weight of the sand affects the loads and velocities measured and if penetration occurs, as in the case of 160mm sabots.
4. Foams can influence the loads measured at different velocities by increasing the thickness. It would require a thickness of 80mm to protect against a 20g PE4 and a thickness of 320mm for the gun based test. However, the total impulse remains the same indicating that although the loads are reduced they act over a longer period of time, which is not desirable.
5. Surrogates used can give a false estimation of the protection offered, with metal surrogates measuring very high loads and gelatine surrogates measuring very low loads. This might lead to over or underestimation of the protection of the boots depending on the surrogate used.

6. Socks are able to influence the protection offered by boots by reducing the depth of penetration by protecting against the abrasive effect of sand. Larger depth of penetration was observed when no sock was used and higher levels of protection can be achieved by using socks with more robust materials. However, just using a sock seems to offer some protection.

8.2 Suggested further work

Suggestions for further work include:

1. Conducting blast tests of larger charge weights and validating the gun based tests against it to see if it is still able to match the damage, loads produced and impulse per unit area values.
2. Testing blast resistant mine boots against both the blast and gun based tests used to determine if the observations made in this PhD are applicable outside of commercially available boots.
3. Conduct a more robust medical analysis of the contamination effect of blast and gun based testing by using more complex surrogates that have a bio – mechanical equivalent of human bone in gelatine.

REFERENCES

Avalle, M., Belingardi, G. and Montanini, R. (2001), "Characterization of polymeric structural foams under compressive impact loading by means of energy – absorption diagram", *International Journal of Impact Engineering*, vol. 25, no. 5, pp. 455 – 472.

Bailey, A. and Murray, S. (1989), "The chemistry and physics of explosions", *Explosives, Propellants, and Pyrotechnics.* London UK: Brassey, pp. 1 – 19.

Bailey, A. and Murray, S. (1989), "The explosion process: detonation shock effects", *Explosives, Propellants, and Pyrotechnics*. London UK: Brassey, pp. 21 – 47.

Banks, E. (ed.) (1997), *Anti – Personnel Mines: A Recognition Guide*, 1st ed, Brassey, London, UK.

Bass, C., Folk, B., Salzar, R., Davis, M., Harris, R., Rountree, M. S., Harcke, T., Rouse, E., Oliver, B. and Sanderson, E. (2004), "Development of a test methodology to evaluate mine protective footwear", Virginia University.

Bergeron, D. and Tremblay, J. (2000), "Canadian research to characterize mine blast output", *16th international MABS symposium*, Oxford, UK.

Bergeron, D., Anderson, I., Coley, G. and Fall, R. (2007), *Assessment of Lower Leg Injury from Land Mine Blast–Phase 2: Follow up Tests with a Modified Frangible Surrogate Lower Leg and Comparison with Cadaver Test Data*, Defence Research Establishment Suffield, Ralston, Canada.

Bergeron, D., Coley, G., Fall, R. and Anderson, I. (2006), *Assessment of lower leg injury from land mine blast—phase 1*, Defence Research and Development Canada, Valcartier, Canada.

Bergeron, D., Walker, R. and Coffey, C. (1998), *Detonation of 100g anti – personnel mine surrogate charges in sand: A test case for computer code validation,* DRES – 668, Defence Research Establishment Suffield, Ralston, Canada.

Berlin, R., Janzon, B., Rybeck, B., Sandegard, J. and Seeman, T. (1977), "Local effects of assault rifle bullets in live tissues. Part II. Further studies in live tissues and relations to some simulant media", *Acta chirurgica Scandinavica.Supplementum*, vol. 477, pp. 5 – 48.

Bolliger, S. A., Thali, M. J., Bolliger, M. J. and Kneubuehl, B. P. (2010), "Gunshot energy transfer profile in ballistic gelatine, determined with computed tomography using the total crack length method", *International journal of legal medicine,* vol. 124, no. 6, pp. 613 – 616.

BSEN1176 (1997), “Playground Equipment Standard”, *Royal Society for the Prevention of Accidents*, British Standard European Norm.

Carruthers, A. (1999), *Scoping study for humanitarian demining technologies,* Defence Research Establishment Suffield.

Chaloner, E. J., McMaster, J. and Hinsley, D. E. (2002), "Principles and problems underlying testing the effectiveness of blast protective footwear", *Journal of the Royal Army Medical Corps,* vol. 148, no. 1, pp. 38 – 43.

Cheeseman, B., Wolf, S., Yen, C. and Skaggs, R. (2006), "Blast simulation of explosives buried in saturated sand", *Fragblast,* vol. 10, no. 1 – 2, pp. 1 – 8.

Coudane, H., Grosdidier, G., Borrelly, J., Sommelet, J., Wack, B., de Ren, G. and Mole, D. (1982), "Experimental study of limb lesions due to hunting weapons", *Acta chirurgica Scandinavica.Supplementum,* vol. 508, pp. 229 – 234.

Coupland, R. M. and Korver, A. (1991), "Injuries from antipersonnel mines: the experience of the International Committee of the Red Cross", *BMJ (Clinical research ed.),* vol. 303, no. 6816, pp. 1509 – 1512.

Cranz, C. (1916), *Lehrbuch der ballistik,* Berlin, Germany.

Cronin, D. and Falzon, C. (2011), "Characterization of 10% ballistic gelatin to evaluate temperature, aging and strain rate effects", *Experimental Mechanics,* vol. 51, no. 7, pp. 1197 – 1206.

Crucq, J. W. B. (1991), *Stochastic computer modeling of wound ballistics,* Doctoral dissertation.

DeMuth Jr, W. and Smith, J. (1966), "High – velocity bullet wounds of muscle and bone: the basis of rational early treatment.", *Journal of Trauma and Acute Care Surgery,* vol. 6, no. 6, pp. 744 – 755.

DePalma, R. G., Burris, D. G., Champion, H. R. and Hodgson, M. J. (2005), "Blast injuries", *New England Journal of Medicine,* vol. 352, no. 13, pp. 1335 – 1342.

Deshpande, V. and Fleck, N. (2000), "High strain rate compressive behaviour of aluminium alloy foams", *International Journal of Impact Engineering,* vol. 24, no. 3, pp. 277 – 298.

DiMaio, V. J. (2015), *Gunshot wounds: practical aspects of firearms, ballistics, and forensic techniques,* CRC press.

Fackler, M. (1987), *What's wrong with the wound ballistics literature, and why.* Letterman Army Institute of Research, Presidio of San Francisco, California.

Fackler, M. (1992), "La Garde's gunshot injuries: an introduction", *Wound Ballistics Review,* vol. 1, pp. 26 – 30.

Fackler, M. (1995), "Review of bullet penetration", *Fight Firearm,* pp. 10 – 13.

Fackler, M. (2001), "Wound profiles", *Wound Ballistics Review,* vol. 5, no. 2, pp. 25 – 38.

Fackler, M. and Kneubuehl, B. (1990), "Applied wound ballistics: what's new and what's true", *Journal of Trauma (China),* vol. 6, pp. 32 – 37.

Fackler, M. L. (1988), "Wound ballistics: a review of common misconceptions", *The Journal of the American Medical Association,* vol. 259, no. 18, pp. 2730 – 2736.

Fackler, M. L. (1996), "Gunshot wound review", *Annals of Emergency Medicine,* vol. 28, no. 2, pp. 194 – 203.

Fackler, M. L. and Malinowski, J. A. (1988), "Ordnance gelatin for ballistic studies. Detrimental effect of excess heat used in gelatin preparation", *The American journal of forensic medicine and pathology,* vol. 9, no. 3, pp. 218 – 219.

Fiserova, D. (2006), *Numerical analysis of buried mine explosions with emphasis on effect of soil properties on loading,* Doctoral dissertation, Defence College of Management and Technology, Cranfield University.

Fujinaka, E. and MacDonald, J. (1966), *Development, Fabrication and Proof testing of Optimum Foot Protection against Anti – personnel mines using a Supplementary Device,* DA19 – 129 QMC – 379(N), Defense Technical Information Center, USA.

Fujinaka, E. and MacDonald, J. (1966), *Research and Development of Blast Protective Footwear, Fabrication and Proof testing,* DA 19 – 129 – QM – 2061 (01 6137), Defense Technical Information Center, USA.

Fung, Y. (2013), *Biomechanics: mechanical properties of living tissues,* Springer Science & Business Media.

Garner, M. J. and Brett, S. J. (2007), "Mechanisms of injury by explosive devices", *Anesthesiology clinics,* vol. 25, no. 1, pp. 147 – 160.

Gelatin Handbook (1982), Gelatine Manufacturers Institute of America, Inc.

Genson, K. W. (2006), *Vehicle shaping for mine blast damage reduction,* Doctoral dissertation, University of Maryland.

Gibson, L. J. and Ashby, M. F. (1999), *Cellular solids: structure and properties,* Cambridge University Press.

Gonzalez, E. G., Corcoran, P. J. and Reyes, R. L. (1974), "Energy expenditure in below – knee amputees: correlation with stump length", *Archives of Physical Medicine and Rehabilitation,* vol. 55, no. 3, pp. 111 – 119.

Hansen, S. T. (2001), "Salvage or amputation after complex foot and ankle trauma", *Orthopedic Clinics of North America,* vol. 32, no. 1, pp. 181 – 186.

Harris, R. M., Rountree, M. S., Griffin, L. V., Hayda, R. A. and Bice, T. (2000), *Final Report of the Lower Extremity Assessment Program (LEAP 99 – 2).* U.S. Army Institute of Surgical Research, Fort Sam Houston.

Harvey, E. N. (1948), "The mechanism of wounding by high velocity missiles", *Proceedings of the American Philosophical Society,* vol. 92, no. 4, pp. 294 – 304.

Harvey, E. N. and Korr, I. M. (1947), "Secondary damage in wounding due to pressure changes accompanying the passage of high velocity missiles", *Surgery,* vol. 21, no. 2, pp. 218 – 239.

Heard, B. J. (2008), "Firearms", *Handbook of Firearms and Ballistics: Examining and Interpreting Forensic Evidence,* 2nd Ed, pp. 1 – 42.

Heffernan, J. (2003), *Pentagon Announces Specific Plans to Use Mines in Iraq*.

Hlady, S. L. (2004), "Effect of soil parameters on landmine blast", *18th International symposium on the Military Aspects of Blast and Shock*, Bad Reichenhall, Germany.

Ho, A. M. (2002), "A simple conceptual model of primary pulmonary blast injury", *Medical hypotheses,* vol. 59, no. 5, pp. 611 – 613.

Holland, S. (2011), The Enhanced Frangible Surrogate Limb Background and Capabilities Document.

Hollerman, J. J., Fackler, M. L., Coldwell, D. M. and Ben – Menachem, Y. (1990), "Gunshot wounds: Bullets, ballistics, and mechanisms of injury", *American Journal of Roentgenology,* vol. 155, no. 4, pp. 685 – 690.

Hooke, R. (2003), *Micrographia: or some physiological descriptions of minute bodies made by magnifying glasses, with observations and inquiries thereupon,* Courier Corporation.

Hopkinson, B. (1915), "British ordnance board minutes 13565", *The National Archives*, Kew, UK.

HPW – TP 0601.02 (1998), *Test Procedure, Ballistic Gelatine Blocks,* H.P. White Laboratories

Hull, J. (1992), "Traumatic amputation by explosive blast: pattern of injury in survivors", *British journal of surgery,* vol. 79, no. 12, pp. 1303 – 1306.

Hull, J. and Cooper, G. (1996), "Pattern and mechanism of traumatic amputation by explosive blast", *Journal of Trauma and Acute Care Surgery,* vol. 40, no. 3, pp. 198 – 205.

Hull, J. B. (1995), *An investigation into the mechanism of traumatic amputation by explosive blast,* Doctor of Medicine dissertation, University of Birmingham, UK.

Hull, J., Bowyer, G., Cooper, G. and Crane, J. (1994), "Pattern of injury in those dying from traumatic amputation caused by bomb blast", *British journal of surgery,* vol. 81, no. 8, pp. 1132 – 1135.

Iremonger, M. (1997), "Physics of detonations and blast waves", *Scientific Foundations of Trauma.* Butterworth – Heinemann, New York, USA, pp. 189 – 199.

Janzon, B., Hull, J. and Ryan, J. (1997), "Projectile – material interactions: soft tissue and bone", *Scientific foundations of trauma*, Butterworth – Heinemann, New York, USA, pp. 37 – 52.

Janzon, B., Schantz, B. and Seeman, T. (1988), "Scale effects in ballistic wounding.", *Journal of Trauma and Acute Care Surgery,* vol. 28, no. 1, pp. 29 – 32.

Jussila, J. (2004), "Preparing ballistic gelatin – review and proposal for a standard method", *Forensic science international,* vol. 141, no. 2, pp. 91 – 98.

Jussila, J. (2005), *Wound ballistic simulation: Assessment of the legitimacy of law enforcement firearms Ammunition by Means of Wound Ballistic Simulation,* Doctoral dissertation, University of Helsinki, Finland.

Karimi, A., Navidbakhsh, M., Yousefi, H. and Alizadeh, M. (2014), "An experimental study on the elastic modulus of gelatin hydrogels using different stress–strain definitions", *Journal of Thermoplastic Composite Materials*.

Keane, M., O'Toole, M. (ed.) (2006), *Miller – Keane Encylopedia & Dictionary of Medicine, Nursing & Allied Health,* 7th Ed, Elsevier.

Kenny, L. (1996), "Mechanical properties of particle stabilized aluminum foam", *Materials Science Forum,* Vol. 217, Trans Tech Publications, pp. 1883 – 1890.

King, C. (1998), *Jane's Mines and Mine Clearance,* 1st Ed, Jane′s Information Group.

Kinsler, L. E., Frey, A. R., Coppens, A. B. and Sanders, J. V. (1999), *Fundamentals of Acoustics,* 4th Ed, Wiley – VCH, pp. 560.

Kluger, Y., Nimrod, A., Biderman, P., Mayo, A. and Sorkin, P. (2007), "The quinary pattern of blast injury", *American journal of disaster medicine,* vol. 2, no. 1, pp. 21 – 25.

Kosten, C. and Zwikker, C. (1939), "Mededel. Rubber – Sticht", *Rubber Chemical Technology Journal,* vol. 12, pp. 105.

La Garde, L. A. (1916), *Gunshot injuries: how they are inflicted, their complications and treatment,* 2nd Ed, W. Wood and Company, New York, USA.

Landmine Monitor Report (2015), *Toward a Mine – Free World,* International Committee to Ban Landmines.

Lankford, J. and Dannemann, K. (1998), "Strain rate effects in porous materials", *Proceedings of the Symposium of the Materials Research Society,* Vol. 521, Cambridge University Press, pp. 103.

Lans, M. (1999), *AP – mine Protective Footwear Exposed to a Contact Explosion with AP no.22C1 Mine,* TNO report PML 1998 – A89, TNO Prins Maurits Laboratory, Rijswijk, Netherlands.

Lewis, R. H., Clark, M. A. and O'Connell, K. J. (1982), "Preparation of gelatin blocks containing tissue samples for use in ballistics research.", *The American journal of forensic medicine and pathology,* vol. 3, no. 2, pp. 181 – 184.

MacPherson, D. (1994), *Bullet penetration: modeling the dynamics and the incapacitation resulting from wound trauma,* 1st Ed, Ballistic Publications, California, USA.

Mah, J. M., Braid, M. P., Fall, R. and Anderson, I. (2007), *The Effect of Standoff on Protection Systems – Experimental Trials with Frangible Surrogate Lower Legs,* DRDC Suffield TM 2007 – 059, Canada.

Martin, E. (2015), *Concise colour medical dictionary,* 5th Ed, Oxford University Press, Oxford, UK.

Martin, E. A. (2010), *A dictionary of science,* Oxford University Press, Oxford, UK.

McGrath, R. (2000), *Landmines and unexploded ordnance: a resource book,* 1st Ed, Pluto Press, Oxford, UK.

McGraw – Hill, P. S. and Parker, S. P. (2003), *McGraw – Hill Dictionary of scientific and technical terms,* 6th Ed, McGraw – Hill.

Merriam – Webster, I. (2014), *Merriam – Webster's dictionary and thesaurus,* Merriam Webster, USA.

Moritsch, B. G. (2000), Association of Firearm and Tool Mark Examiners Glossary, www.afte.org.

Mukai, T., Kanahashi, H., Miyoshi, T., Mabuchi, M., Nieh, T. and Higashi, K. (1999), "Experimental study of energy absorption in a close – celled aluminum foam under dynamic loading", *Scripta Materialia*, vol. 40, no. 8, pp. 921 – 927.

Muschek, R. C. (1998), *Evaluation of the Mechanical Properties and Effectiveness of Countermine Boots.*, Master's Thesis, Naval Postgraduate School, California.

Muschek, R. C., King, Q. M. and Kwon, Y. W. (1997), *Evaluation of the Mechanical Properties of Countermine Boots,* NPS – ME – 97 – 007, Naval Postgraduate School, California.

NATO TR – HFM – 089 (2004), *Test Methodologies for Personal Protective Equipment Against Anti – Personnel Mine Blast,* RTO Technical Report, North Atlantic Treaty Organization.

Nechaev, E., Gritsanov, A., Fomin, N. and Minnullin, I. (1984), *Mine blast trauma,* Ministry of Public Health and Medical Industry, St Petersberg, Russia.

Ngo, T., Mendis, P., Gupta, A. and Ramsay, J. (2007), "Blast loading and blast effects on structures–an overview", *Electronic Journal of Structural Engineering,* vol. 7, pp. 76 – 91.

Nicol D. J. (2011), *Test Methods for Anti – Personnel Mine Boots*, Master's Thesis, Cranfield Defence and Security, Cranfield University, UK.

Payne, L. (1997), "Wound ballistics research before 1945", *Scientific foundations of trauma,* Butterworth Heinemann, Oxford, UK, pp. 3 – 11.

Pearsall, J. (1999), *Oxford Concise English Dictionary,* 10th Ed, Oxford University Press, Oxford, UK.

Peters, C. E. (1990), "A mathematical – physical model of wound ballistics", *Journal of Trauma (China),* vol. 6, no. 2, pp. 308 – 318.

Phillips, Y. Y. (1986), "Primary blast injuries", *Annals of Emergency Medicine*, vol. 15, no. 12, pp. 1446 – 1450.

Physicians for Human Rights (1993), *Landmines: A Deadly Legacy*, The Arms Project of Human Rights Watch & Physicians for Human Rights.

Protective footwear US Patent no. US20060000117 A1, January 2006. Available at: https://www.google.com/patents/US20060000117 (accessed July 2016).

Ragsdale, B. D. and Josselson, A. (1988), "Predicting temporary cavity size from radial fissure measurements in ordnance gelatin.", *Journal of Trauma and Acute Care Surgery*, vol. 28, no. 1, pp. 5 – 9.

Ramasamy, A., Hill, A. M., Hepper, A. E., Bull, A. M. and Clasper, J. C. (2009), "Blast mines: physics, injury mechanisms and vehicle protection", *Journal of the Royal Army Medical Corps*, vol. 155, no. 4, pp. 258 – 264.

Rigby, S. E. and Sielicki, P. W. (2015), "An investigation of TNT equivalence of hemispherical PE4 charges", *Engineering Transactions*, vol. 62, no. 4, pp. 423–435.

Rountree, M. S. and Harris, R. M. (2000), "Countering the Global Landmine Epidemic Through Basic Scientific Research", *Journal of Conventional Weapons Destruction*, vol. 4, no. 2, pp. 13.

Rousselot, *Gelatine bloom*, 2016, available at:http://www.rousselot.com/en/rousselotgelatine/gelatine – characteristics/definitions/gelatine – bloom/ (accessed July 2016).

Rutty, G., Boyce, P., Robinson, C., Jeffery, A. and Morgan, B. (2008), "The role of computed tomography in terminal ballistic analysis", *International journal of legal medicine*, vol. 122, no. 1, pp. 1 – 5.

Schyma, C. and Madea, B. (2012), "Evaluation of the temporary cavity in ordnance gelatine", *Forensic science international*, vol. 214, no. 1, pp. 82 – 87.

Schyma, C. W. A. (2010), "Colour contrast in ballistic gelatine", *Forensic science international*, vol. 197, no. 1, pp. 114 – 118.

Sellier, K. G. and Kneubuehl, B. P. (1994), *Wound ballistics and the scientific background*, Elsevier Health Sciences.

Sepulveda, P. and Binner, J. (1999), "Processing of cellular ceramics by foaming and in situ polymerisation of organic monomers", *Journal of the European Ceramic Society*, vol. 19, no. 12, pp. 2059 – 2066.

Serway, R. A. and Jewett, J. W. (2013), *Physics for scientists and engineers with modern physics*, 9th Ed, Nelson Education.

Smith, D. (2003), "Transtibial Amputations: Successes and Challenges", *inMotion,* vol. 13, no. 4, pp. 57 – 63.

Smith, P. D. and Hetherington, J. G. (1994), *Blast and ballistic loading of structures,* Digital Press.

Stuhmiller, J. H., Phillips, Y. and Richmond, D. (1991), "The physics and mechanisms of primary blast injury", *Conventional Warfare: Ballistic, Blast, and Burn Injuries:* Department of the Army, Office of the Surgeon General, pp. 241 – 270.

Tactical Briefs (2000), *A simplified 10% Ordnance Gelatine Preparation and Test Procedure,* Firearms Tactical Institute.

Thali, M. J., Kneubuehl, B., Dirnhofer, R. and Zollinger, U. (2001), "Body models in forensic ballistics: reconstruction of a gunshot injury to the chest by bullet fragmentation after shooting through a finger", *Forensic science international,* vol. 123, no. 1, pp. 54 – 57.

Thali, M. J., Kneubuehl, B., Zollinger, U. and Dirnhofer, R. (2002), "The “skin–skull–brain model”: a new instrument for the study of gunshot effects", *Forensic science international,* vol. 125, no. 2, pp. 178 – 189.

Thali, M. J., Kneubuehl, B., Zollinger, U. and Dirnhofer, R. (2002), "A study of the morphology of gunshot entrance wounds, in connection with their dynamic creation, utilizing the “skin–skull–brain model”", *Forensic science international,* vol. 125, no. 2, pp. 190 – 194.

Thomson, W. S. (1887), "On the division of space with minimum partitional area", *Acta Mathematica,* vol. 11, no. 1 – 4, pp. 121 – 134.

Traugh, G. H., Corcoran, P. J. and Reyes, R. L. (1975), "Energy expenditure of ambulation in patients with above – knee amputations", *Archives of Physical Medicine and Rehabilitation,* vol. 56, no. 2, pp. 67 – 71.

Tremblay, J. (1998), *Impulse on blast deflectors from a landmine explosion,* Defence Research Establishment, Canada.

Tremblay, J., Bergeron, D. and Gonzalez, R. (1998), *Protection of Soft – Skinned Vehicle Occupants from Landmine Effects,* The Technical Cooperation Program (TT CP), Defence Research Establishment, Canada.

Trimble, K. and Clasper, J. (2001), "Anti – personnel mine injury; mechanism and medical management", *Journal of the Royal Army Medical Corps,* vol. 147, no. 1, pp. 73 – 79.

Van Bree, J. and van der Heiden, N. (1996), "Behind armour pressure profiles in tissue simulant", *Personal Armour Systems Symposium,* Vol. 96.

Van Bree, J. L. and Fairlie, G. (1999), "Compression wave experimental and numerical studies in gelatine behind armour", *18th International symposium on ballistics,* San Antonio, USA.

Van der Horst, M., Dijkstra, M., van de Kasteele, R. and Luiting, K. M. (2008), *Blast Performance of Commercially Available Demining Footwear: A Summary of Experimental Trials on Surrogate Legs,* TNO Report TNO – DV 2008 A379.

Westine, P., Morris, B., Cox, P. and Polch, E. (1985), *Development of computer program for floor plate response from land mine explosions*, Technical Report No. 13045, US Army – Automotive Command.

Wolf, S. J., Bebarta, V. S., Bonnett, C. J., Pons, P. T. and Cantrill, S. V. (2009), "Blast injuries", *The Lancet,* vol. 374, no. 9687, pp. 405 – 415.

Wolfenden, A. (1990), *Dynamic elastic modulus measurements in materials,* ASTM International.

Zhang, J., Kikuchi, N., Li, V., Yee, A. and Nusholtz, G. (1998), "Constitutive modeling of polymeric foam material subjected to dynamic crash loading", *International Journal of Impact Engineering,* vol. 21, no. 5, pp. 369 – 386.

APPENDIX A – Method for the preparation of 20% (by mass) gelatine (10 legs – 45kg gelatine)

Equipment required:

2 buckets (15L each)	2 mixing trugs (40L each)
Temperature probe	Industrial hand held mixer
Arm length latex gloves	1L Pyrex jug
Weighing scale	2 Urns (20L each)
Type 3 ballistic gelatine (Gelita gelatine)	Water
10 Dunlop Wellington boots	Silicone Mould release spray
Cinnamon oil	Nylon rope
200mm cut PVC pipes	

Method:

All the equipment needs to be cleaned prior to use, this includes the urns that might need to be washed thoroughly to remove the lime scale build – up. Fill and switch on the urns in advance to give time for the water to reach 70^{o}C.

1. Loops need to be cut into the Wellington boots at the top and tie the nylon rope through it. Suspend the Wellington boots on a horizontal bar using the nylon ropes.
2. In a well ventilated room apply a coating of the silicone mould release spray to the interior of the boots.
3. Weigh 0.9kg of gelatine powder in one of the buckets.
4. In one bucket mix hot and cold up to a weight of 3.6kg ensuring that the temperature is in between 60 – 65^{o}C. Transfer this into the empty trug.
5. Add the weighed gelatine powder to the hot water and mix using the hand held mixer. Once the gelatine is dissolved transfer it to the other empty trug.
6. Repeat steps 3 – 5 another 9 times. At the end add a few drops of cinnamon oil and let it stand for a few minutes.
7. Pour the gelatine into the suspended Wellington boots using the Pyrex jug.
8. If required to be attached to the test rig, insert PVC pipes into the gelatine.

9. Leave the Wellington boots to suspend overnight
10. The following morning place the Wellington boots into a refrigerator (set at $4^{o}C$) and leave for 24 hours.
11. After 24 hours if required, the gelatine leg can be cut out of the Wellington boots by scoring the surface along the seams and then gently separating it from the gelatine.

APPENDIX B – Explanation of statistical methods used

The terms and statistical method used as part of the thesis will be defined and explained in this section. This will be followed by a detailed breakdown of how the statistical analysis was conducted. The definitions below assume that numerical data has been collected, which is referred to as the sample.

Mean – it refers to the central value for a set of data, which is defined as the sum of all values in the data set divided by the number of values (n) in it (Harraway, 1997).

Standard deviation (s.d.) – it is a measure of variation of a set of data values. It describes the distance by which the typical group member differs from the mean (Schmidt, 1979). A large s.d. indicates a large range of data points, with a small s.d. meaning the data points are closer to the mean.

Analysis of Variance (ANOVA) – it provides a statistical test of whether or not the means of several groups are equal. ANOVA works on four basic assumptions:

1. The expected values of error are zero due to the fact that although the amount of time for each of the trials is similar for their corresponding packs, differences in the data may be observed in the same layers which may be attributed to certain other factors beyond human control.
2. The variance of all errors is equal to each other.
3. The errors are independent.
4. They are normally distributed.

Thus, estimates of the amount of variation due to assignable causes (or variance between the samples) as well as due to chance causes (or variance within the samples) are obtained separately and compared using an F – test and conclusions are drawn using the value of F (Harraway, 1997).

Sum of square (SS) – it is the sum of the squared deviation scores (Schmidt, 1979).

Degrees of freedom (d.f.) – it is a characteristic of the sample statistic that determines the appropriate sampling distribution (Schmidt, 1979)

Mean square – Mean squares are estimates of variance across groups (Harraway, 1997). They are used in ANOVA and are calculated as a sum of squares divided by its degrees of freedom.

Significance – A significant result is reported when the null hypothesis has been rejected (Coolidge, 2006)

Confidence levels / p≤ – it is a term used to signify the confidence that the given interval includes a particular parameter based on the confidence interval estimates of all parameter values (Schmidt, 1979).

Normality of data – it is a check to see if the data is normally distributed, that is the data has a bell – shaped curve (Coolidge, 2006).

ANOVA

The velocity data for paper sabots will now be analysed with each stage of the ANOVA analysis explained.

Table B.1: A sub – set of the result of ballistic testing to determine cause of penetration

Slug (Yes/No)	Velocity (m/s)
Yes	360.52
Yes	407.48
Yes	360.99
Yes	336.96
Yes	433.16
Yes	318.46
Yes	340.72
Yes	362.04
Yes	304.69
Yes	330.25
No	439.19
No	411.49
No	553.72
No	460.05
Mean	387.12

Step 1: The data from table B1 can be split into the following components:

a. General level effect
b. Slug effect

c. Experimental error (residual error)

Step 2: Estimates are then calculated for this effect:

The general level effect is taken as the overall mean = 387.12

The effects of slug are the differences between the overall mean and the two slug means:

For Slug = Yes 354.97-387.12 = -32.15

For Slug = No 466.11-387.12 = 78.99

Step 3: Estimates for the experimental error (residual effect) are obtained by subtracting the general level effect and slug effect from each data value. Hence, for each data value,

407.48; 407.48 - 387.12 + 32.15 = **52.51** 330.25; 330.25 - 387.12 + 32.15 = **-24.72**

360.99; 360.99 - 387.12 + 32.15 = **6.02** 362.04; 362.04 - 387.12 + 32.15 = **7.07**

336.96; 336.96 - 387.12 + 32.15 = **-18.01** 360.52; 360.52 - 387.12 + 32.15 = **5.55**

433.16; 433.16 - 387.12 + 32.15 = **78.19** 553.72; 553.72 - 387.12 - 78.99 = **87.61**

318.46; 318.46 - 387.12 + 32.15 = **-36.51** 460.05; 460.05 - 387.12 - 78.99 = **-6.06**

340.72; 340.72 - 387.12 + 32.15 = **-14.25** 439.19; 439.19 - 387.12 - 78.99 = **-26.92**

304.69; 304.69 - 387.12 + 32.15 = **-50.28** 411.49; 411.49 - 387.12 - 78.99 = **-54.62**

Step 4: Separating the sum of squares is performed by:

$\sum$ (data values)^2 $= (407.48)^2 + (360.99)^2 + (336.96)^2 \ldots + (411.49)^2$

$= 2158442.66$

$\sum$ (general values)^2 $= 14\ (387.12)^2$

$= 2098097.49$

$\sum$ (Slug effects)^2 $= 10\ (32.15)^2 + 4\ (78.99)^2$

$= 35294.09$

$\sum$ (Residual effects)^2 $= (52.51)^2 + (6.02)^2 + (-18.01)^2 \ldots + (87.61)^2$

$= 25407.81$

It can be shown that:

$\sum$ (data values)^2 $= \sum$ (general values)^2 + $\sum$ (Slug effects)^2 + $\sum$ (Residual effects)^2

2158442.66 = 2098097.49 + 35294.09 + 25407.81

Step 5: The degrees of freedom used to divide the sums of squares to produce the mean squares are:

- General level effect d.f. = 1
- Slug effect d.f. = 1
- Residual d.f. = 14 - 1 - 1 = 12

Thus the mean squares are:

Slug effect = 35294.09 ÷ 1 = 35294.09

Residual effect = 25407.81 ÷ 12 = 2117.32

Step 6: Calculating the F values for slug effect = 35294.09 ÷ 2117.32

= 16.67

Step 7: Calculating significance is performed to see if the F statistic is large enough to indicate sample differences. This is done by comparing the observed F statistic with a critical value from an F table with 5%, 0.5%, and 0.1% level of significance. The number of d.f. for slug effect mean square is V_1 while V_2 is the number of d.f. for the residual effect mean square.

At 0.5% significance level for slug effect; $V_1 = 1$ and $V_2 = 12$, Pr ($F_{1, 12} = 11.75$) = 0.005. The F statistic = 16.67 which is greater than 11.75, and therefore significant at the 0.5% level. From the stage above, the following analysis of variance can be produced:

Table B.2: Analysis of variance for ballistic test for all samples using paper sabots evaluating slug effect on velocities

Source of	SS	d.f.	Mean	F	Sig.	p≤

variation			square			
Slug	35294.09	1	35294.09	16.67	0.001	0.005
Error	25407.81	12	2117.32			

Result showed that the formation of the slug had a highly significant effect on the velocities recorded ($F_{1,\ 12}$ = 16.67, p≤0.005). This indicates that there is strong evidence that a difference between the data value means is present when a slug is and is not formed. This indicates that the null hypothesis of the means being equal for the presence and absence of a slug should be rejected.

References

Coolidge, F. L., Statistics – A gentle introduction, 2nd Edition, 2006.

Harraway, J., Introductory statistical methods for biological, health and social sciences,1997.

Schmidt, M. J., Understanding and using statistics – Basic concepts, 2nd Edition, 1979.

APPENDIX C – Kistler load washer specification

Table C.1: Specification of load washers used during the thesis

Load washer	**9031A**	**9051A**	**9061A**
Measuring range (kN)	0 – 60	0 – 120	0 – 200
Overload (kN)	72	144	240
Capacity (pF)	54	64	148
Internal diameter (mm)	13	21	26.5
External diameter (mm)	28.5	40.5	52.5
Height (mm)	11	13	15
Weight (g)	36	80	157
Sensitivity (pC/N)		4.3	
Operating temperature (^{o}C)		-196 – 200	

APPENDIX D – Raw data from foam tests

Table D.1: Raw data for HD45

Sample Name	Peak striker force	Peak anvil force	Peak C.I striker	Peak C.I anvil
HD 45_1 Layer_1m/s – TR1	0.43	0.42	4.88	4.72
HD 45_1 Layer_1m/s – TR1 – Reused	0.49	0.48	5.08	4.84
HD 45_1 Layer_1m/s – TR2	0.44	0.43	4.92	4.67
HD 45_1 Layer_1m/s – TR2 – Reused	0.51	0.49	5.12	4.90
HD 45_1 Layer_1m/s – TR3	0.43	0.42	4.91	4.69
HD 45_1 Layer_1m/s – TR3 – Reused	0.50	0.48	5.08	4.83
HD 45_1 Layer_2m/s – TR1	3.45	3.23	9.60	9.04
HD 45_1 Layer_2m/s – TR1 – Reused	4.52	4.22	10.00	9.30
HD 45_1 Layer_2m/s – TR2	3.22	3.00	9.57	9.03
HD 45_1 Layer_2m/s – TR2 – Reused	4.23	3.95	9.90	9.29
HD 45_1 Layer_2m/s – TR3	3.23	3.03	9.60	9.10
HD 45_1 Layer_2m/s – TR3 – Reused	4.24	3.96	9.91	9.30
HD 45_1 Layer_5m/s – TR1	N/A	N/A	N/A	N/A
HD 45_1 Layer_5m/s – TR1 – Reused	N/A	N/A	N/A	N/A
HD 45_1 Layer_5m/s – TR2	N/A	N/A	N/A	N/A
HD 45_1 Layer_5m/s – TR2 – Reused	N/A	N/A	N/A	N/A
HD 45_1 Layer_5m/s – TR3	N/A	N/A	N/A	N/A
HD 45_1 Layer_5m/s – TR3 – Reused	N/A	N/A	N/A	N/A
	N/A	N/A	N/A	N/A
HD 45_2 Layer_1m/s – TR1	0.26	0.26	4.88	4.70
HD 45_2 Layer_1m/s – TR1 – Reused	0.28	0.28	5.08	4.90
HD 45_2 Layer_1m/s – TR2	0.26	0.26	4.86	4.69
HD 45_2 Layer_1m/s – TR2 – Reused	0.28	0.28	5.09	4.87
HD 45_2 Layer_1m/s – TR3	0.26	0.26	4.91	4.69
HD 45_2 Layer_1m/s – TR3 – Reused	0.29	0.28	5.12	4.86
HD 45_2 Layer_2m/s – TR1	0.93	0.88	9.57	9.12
HD 45_2 Layer_2m/s – TR1 – Reused	1.23	1.16	10.04	9.48
HD 45_2 Layer_2m/s – TR2	0.90	0.86	9.54	9.10
HD 45_2 Layer_2m/s – TR2 –	1.12	1.06	9.92	9.39

Reused				
HD 45_2 Layer_2m/s – TR3	0.93	0.89	9.58	9.09
HD 45_2 Layer_2m/s – TR3 – Reused	1.16	1.11	9.91	9.41
HD 45_2 Layer_5m/s – TR1	N/A	N/A	N/A	N/A
HD 45_2 Layer_5m/s – TR1 – Reused	N/A	N/A	N/A	N/A
HD 45_2 Layer_5m/s – TR2	N/A	N/A	N/A	N/A
HD 45_2 Layer_5m/s – TR2 – Reused	N/A	N/A	N/A	N/A
HD 45_2 Layer_5m/s – TR3	N/A	N/A	N/A	N/A
HD 45_2 Layer_5m/s – TR3 – Reused	N/A	N/A	N/A	N/A
	N/A	N/A	N/A	N/A
HD 45_5 Layer_1m/s – TR1	0.19	0.20	5.07	4.88
HD 45_5 Layer_1m/s – TR1 – Reused	0.19	0.19	5.27	5.06
HD 45_5 Layer_1m/s – TR2	0.19	0.19	5.10	4.92
HD 45_5 Layer_1m/s – TR2 – Reused	0.19	0.19	5.35	5.17
HD 45_5 Layer_1m/s – TR3	0.19	0.20	5.06	4.81
HD 45_5 Layer_1m/s – TR3 – Reused	0.19	0.19	5.22	5.08
HD 45_5 Layer_2m/s – TR1	0.36	0.35	9.71	9.27
HD 45_5 Layer_2m/s – TR1 – Reused	0.41	0.40	10.12	9.62
HD 45_5 Layer_2m/s – TR2	0.35	0.34	9.61	9.12
HD 45_5 Layer_2m/s – TR2 – Reused	0.40	0.39	9.99	9.53
HD 45_5 Layer_2m/s – TR3	0.35	0.34	9.64	9.16
HD 45_5 Layer_2m/s – TR3 – Reused	0.40	0.39	10.01	9.57
HD 45_5 Layer_5m/s – TR1	6.32	5.80	23.99	22.14
HD 45_5 Layer_5m/s – TR1 – Reused	8.63	7.88	24.47	22.57
HD 45_5 Layer_5m/s – TR2	5.39	4.97	23.47	21.82
HD 45_5 Layer_5m/s – TR2 – Reused	8.01	7.34	24.31	22.45
HD 45_5 Layer_5m/s – TR3	5.39	4.98	23.37	21.82
HD 45_5 Layer_5m/s – TR3 – Reused	8.05	7.38	24.3	22.42

Table D.2: Raw data for HD 80

Sample Name	Peak striker force	Peak anvil force	Peak C.I striker	Peak C.I anvil
HD 80_1 Layer_1m/s – TR1	0.77	0.73	4.15	4.00
HD 80_1 Layer_1m/s – TR1 – Reused	0.74	0.70	4.31	4.09
HD 80_1 Layer_1m/s – TR2	0.77	0.72	4.16	3.98
HD 80_1 Layer_1m/s – TR2 – Reused	0.70	0.67	4.29	4.11
HD 80_1 Layer_1m/s – TR3	0.78	0.75	4.16	4.01
HD 80_1 Layer_1m/s – TR3 – Reused	0.73	0.70	4.29	4.16
HD 80_1 Layer_2m/s – TR1	1.16	1.12	7.91	7.56
HD 80_1 Layer_2m/s – TR1 – Reused	1.73	1.63	8.52	8.10
HD 80_1 Layer_2m/s – TR2	1.15	1.10	7.94	7.56
HD 80_1 Layer_2m/s – TR2 – Reused	1.70	1.61	8.49	8.08
HD 80_1 Layer_2m/s – TR3	1.18	1.14	7.92	7.51
HD 80_1 Layer_2m/s – TR3 – Reused	1.80	1.71	8.54	8.15
HD 80_1 Layer_5m/s – TR1	29.71	27.34	23.04	20.14
HD 80_1 Layer_5m/s – TR1 – Reused	N/A	N/A	N/A	N/A
HD 80_1 Layer_5m/s – TR2	27.80	25.51	22.39	19.88
HD 80_1 Layer_5m/s – TR2 – Reused	N/A	N/A	N/A	N/A
HD 80_1 Layer_5m/s – TR3	28.72	26.45	22.48	20.07
HD 80_1 Layer_5m/s – TR3 – Reused	N/A	N/A	N/A	N/A
HD 80_2 Layer_1m/s – TR1	0.75	0.73	4.34	4.15
HD 80_2 Layer_1m/s – TR1 – Reused	0.70	0.67	4.46	4.25
HD 80_2 Layer_1m/s – TR2	0.75	0.72	4.36	4.16
HD 80_2 Layer_1m/s – TR2 – Reused	0.71	0.68	4.47	4.27
HD 80_2 Layer_1m/s – TR3	0.76	0.73	4.36	4.16
HD 80_2 Layer_1m/s – TR3 – Reused	0.71	0.68	4.44	4.25
HD 80_2 Layer_2m/s – TR1	0.83	0.78	7.96	7.54
HD 80_2 Layer_2m/s – TR1 – Reused	0.87	0.83	8.35	8.00
HD 80_2 Layer_2m/s – TR2	0.86	0.82	7.95	7.55
HD 80_2 Layer_2m/s – TR2 – Reused	0.87	0.84	8.33	7.99

HD 80_2 Layer_2m/s – TR3	0.84	0.80	7.94	7.56
HD 80_2 Layer_2m/s – TR3 – Reused	0.87	0.84	8.37	7.95
HD 80_2 Layer_5m/s – TR1	9.95	9.13	20.34	18.77
HD 80_2 Layer_5m/s – TR1 – Reused	20.48	18.57	22.70	20.33
HD 80_2 Layer_5m/s – TR2	8.99	8.25	20.09	18.57
HD 80_2 Layer_5m/s – TR2 – Reused	19.79	17.98	22.47	20.31
HD 80_2 Layer_5m/s – TR3	9.14	8.43	19.98	18.57
HD 80_2 Layer_5m/s – TR3 – Reused	19.83	18.03	22.54	20.29
HD 80_5 Layer_1m/s – TR1	0.64	0.61	4.69	4.55
HD 80_5 Layer_1m/s – TR1 – Reused	0.62	0.60	4.80	4.60
HD 80_5 Layer_1m/s – TR2	0.66	0.63	4.72	4.56
HD 80_5 Layer_1m/s – TR2 – Reused	0.64	0.61	4.84	4.64
HD 80_5 Layer_1m/s – TR3	0.65	0.63	4.73	4.54
HD 80_5 Layer_1m/s – TR3 – Reused	0.62	0.61	4.80	4.60
HD 80_5 Layer_2m/s – TR1	0.76	0.73	8.36	7.93
HD 80_5 Layer_2m/s – TR1 – Reused	0.70	0.68	8.66	8.31
HD 80_5 Layer_2m/s – TR2	0.79	0.75	8.41	8.06
HD 80_5 Layer_2m/s – TR2 – Reused	0.71	0.68	8.71	8.26
HD 80_5 Layer_2m/s – TR3	0.79	0.75	8.39	7.97
HD 80_5 Layer_2m/s – TR3 – Reused	0.69	0.67	8.62	8.22
HD 80_5 Layer_5m/s – TR1	1.46	1.38	19.67	18.61
HD 80_5 Layer_5m/s – TR1 – Reused	2.44	2.29	21.13	19.86
HD 80_5 Layer_5m/s – TR2	1.45	1.37	19.63	18.48
HD 80_5 Layer_5m/s – TR2 – Reused	2.47	2.31	21.12	19.85
HD 80_5 Layer_5m/s – TR3	1.42	1.34	19.45	18.39
HD 80_5 Layer_5m/s – TR3 – Reused	2.41	2.27	21.03	19.79

Table D.3: Raw data for HD 115

Sample Name	Peak striker force	Peak anvil force	Peak C.I striker	Peak C.I anvil
HD 115_1 Layer_1m/s – TR1	2.10	1.85	4.14	3.94
HD 115_1 Layer_1m/s – TR1 – Reused	1.84	1.67	4.20	3.96
HD 115_1 Layer_1m/s – TR2	1.96	1.80	4.17	3.94
HD 115_1 Layer_1m/s – TR2 – Reused	1.89	1.74	4.22	3.98
HD 115_1 Layer_1m/s – TR3	1.94	1.77	4.17	3.93
HD 115_1 Layer_1m/s – TR3 – Reused	1.90	1.74	4.23	4.00
HD 115_1 Layer_2m/s – TR1	2.44	1.96	7.40	6.95
HD 115_1 Layer_2m/s – TR1 – Reused	1.92	1.83	7.67	7.26
HD 115_1 Layer_2m/s – TR2	2.31	1.81	7.34	6.94
HD 115_1 Layer_2m/s – TR2 – Reused	1.85	1.75	7.68	7.27
HD 115_1 Layer_2m/s – TR3	2.36	1.94	7.34	6.91
HD 115_1 Layer_2m/s – TR3 – Reused	1.96	1.85	7.65	7.25
HD 115_1 Layer_5m/s – TR1	17.50	16.02	19.40	17.60
HD 115_1 Layer_5m/s – TR1 – Reused	31.26	27.84	22.57	19.78
HD 115_1 Layer_5m/s – TR2	17.07	15.56	19.25	17.48
HD 115_1 Layer_5m/s – TR2 – Reused	31.85	28.50	22.75	20.05
HD 115_1 Layer_5m/s – TR3	17.59	15.77	19.28	17.45
HD 115_1 Layer_5m/s – TR3 – Reused	32.22	28.89	22.88	20.16
HD 115_2 Layer_1m/s – TR1	1.70	1.59	4.41	4.15
HD 115_2 Layer_1m/s – TR1 – Reused	1.72	1.61	4.51	4.26
HD 115_2 Layer_1m/s – TR2	1.73	1.63	4.43	4.14
HD 115_2 Layer_1m/s – TR2 – Reused	1.73	1.63	4.49	4.26
HD 115_2 Layer_1m/s – TR3	1.78	1.67	4.42	4.21
HD 115_2 Layer_1m/s – TR3 – Reused	1.74	1.63	4.46	4.22
HD 115_2 Layer_2m/s – TR1	2.00	1.85	7.66	7.24
HD 115_2 Layer_2m/s – TR1 – Reused	1.82	1.74	7.91	7.44
HD 115_2 Layer_2m/s – TR2	2.03	1.85	7.68	7.20
HD 115_2 Layer_2m/s – TR2 – Reused	1.83	1.73	7.95	7.49

HD 115_2 Layer_2m/s – TR3	1.96	1.85	7.69	7.24
HD 115_2 Layer_2m/s – TR3 – Reused	1.84	1.75	7.91	7.45
HD 115_2 Layer_5m/s – TR1	3.98	3.76	17.77	16.49
HD 115_2 Layer_5m/s – TR1 – Reused	9.63	8.86	19.59	17.83
HD 115_2 Layer_5m/s – TR2	4.24	3.98	17.70	16.56
HD 115_2 Layer_5m/s – TR2 – Reused	10.64	9.76	19.65	17.94
HD 115_2 Layer_5m/s – TR3	4.21	3.95	17.70	16.55
HD 115_2 Layer_5m/s – TR3 – Reused	10.68	9.82	19.63	18.05
HD 115_5 Layer_1m/s – TR1	1.23	1.16	4.53	4.27
HD 115_5 Layer_1m/s – TR1 – Reused	1.30	1.23	4.71	4.45
HD 115_5 Layer_1m/s – TR2	1.25	1.17	4.63	4.32
HD 115_5 Layer_1m/s – TR2 – Reused	1.29	1.21	4.71	4.43
HD 115_5 Layer_1m/s – TR3	1.28	1.21	4.58	4.32
HD 115_5 Layer_1m/s – TR3 – Reused	1.34	1.27	4.77	4.49
HD 115_5 Layer_2m/s – TR1	1.84	1.73	8.32	7.85
HD 115_5 Layer_2m/s – TR1 – Reused	1.79	1.69	8.46	7.96
HD 115_5 Layer_2m/s – TR2	1.83	1.73	8.25	7.79
HD 115_5 Layer_2m/s – TR2 – Reused	1.78	1.67	8.45	7.94
HD 115_5 Layer_2m/s – TR3	1.82	1.72	8.25	7.81
HD 115_5 Layer_2m/s – TR3 – Reused	1.78	1.67	8.49	7.95
HD 115_5 Layer_5m/s – TR1	1.99	1.79	18.40	16.99
HD 115_5 Layer_5m/s – TR1 – Reused	2.14	2.02	18.93	17.58
HD 115_5 Layer_5m/s – TR2	2.07	1.87	17.85	16.79
HD 115_5 Layer_5m/s – TR2 – Reused	2.12	2.00	18.83	17.70
HD 115_5 Layer_5m/s – TR3	2.09	1.90	18.05	16.73
HD 115_5 Layer_5m/s – TR3 – Reused	2.23	2.10	19.16	17.71

Table D.4: Raw thickness and hardness data

HD 45	Thickness	Hardness
1	9.01	17
2	9.66	17
3	9.44	17
4	9.3	18
5	9.46	19
6	9.36	19
7	9.48	19
8	9.38	18
9	9.27	18
10	9.49	18
Average	9.385	18
S.D.	0.16311	0.816497
HD 80	**Thickness**	**Hardness**
1	10.18	45
2	10.64	46
3	10.62	46
4	10.77	45
5	10.35	44
6	10.39	44
7	10.84	45
8	10.88	45
9	10.49	45
10	10.55	44
Average	10.571	44.9
S.D.	0.213563	0.737865
HD 115	**Thickness**	**Hardness**
1	9.95	58
2	9.78	59
3	9.64	58
4	9.76	59
5	9.75	59
6	9.79	60
7	9.77	59
8	9.62	59
9	9.71	58
10	9.8	60
Average	9.757	58.9
S.D.	0.086954	0.737865

Table D.5: Processed data of drop tower

Foam	Velocity (m/s)	Layers	Mean striker force (kN)	s.d. (kN)	Mean anvil force (kN)	s.d. (kN)	Total impulse – striker (N.s)	s.d. (N.s)	Total impulse – anvil (N.s)	s.d. (N.s)
HD 115	1	1 – New	1.87	0.03	1.72	0.04	4.22	0.02	3.98	0.02
		1 – Used	2.00	0.08	1.81	0.04	4.16	0.02	3.94	0.01
		2 – New	1.73	0.01	1.62	0.01	4.49	0.02	4.25	0.02
		2 – Used	1.74	0.04	1.63	0.04	4.42	0.01	4.17	0.04
		5 – New	1.25	0.03	1.18	0.03	4.58	0.05	4.30	0.03
		5 – Used	1.31	0.03	1.24	0.03	4.73	0.04	4.46	0.03
	2	1 – New	1.91	0.06	1.81	0.05	7.67	0.01	7.26	0.01
		1 – Used	2.37	0.07	1.90	0.08	7.36	0.03	6.93	0.02
		2 – New	1.83	0.01	1.74	0.01	7.92	0.02	7.46	0.03
		2 – Used	2.00	0.03	1.85	0.00	7.68	0.02	7.23	0.02

		5 – New	1.78	0.01	1.68	0.01	8.46	0.02	7.95	0.01
		5 – Used	1.83	0.01	1.73	0.01	8.27	0.04	7.82	0.03
	5	1 – New	17.39	0.28	15.78	0.23	19.31	0.08	17.51	0.08
		1 – Used	31.77	0.48	28.41	0.53	22.73	0.16	20.00	0.20
		2 – New	4.14	0.15	3.90	0.12	17.73	0.04	16.53	0.04
		2 – Used	10.32	0.59	9.48	0.51	19.62	0.03	17.94	0.11
		5 – New	2.05	0.05	1.85	0.06	18.10	0.28	16.84	0.14
		5 – Used	2.17	0.06	2.04	0.05	18.97	0.17	17.66	0.07
HD 80	1	1 – New	0.72	0.02	0.69	0.02	4.30	0.01	4.12	0.04
		1 – Used	0.77	0.01	0.73	0.02	4.16	0.01	4.00	0.02
		2 – New	0.71	0.01	0.68	0.01	4.46	0.02	4.26	0.01
		2 – Used	0.75	0.01	0.73	0.01	4.35	0.01	4.16	0.01
		5 –	0.63	0.01	0.61	0.01	4.81	0.02	4.61	0.02

		New								
		5 – Used	0.65	0.01	0.62	0.01	4.71	0.02	4.55	0.01
	2	1 – New	1.16	0.02	1.12	0.02	7.92	0.02	7.54	0.03
		1 – Used	1.74	0.05	1.65	0.05	8.52	0.03	8.11	0.04
		2 – New	0.84	0.02	0.80	0.02	7.95	0.01	7.55	0.01
		2 – Used	0.87	0.00	0.84	0.01	8.35	0.02	7.98	0.03
		5 – New	0.70	0.01	0.68	0.01	8.66	0.05	8.26	0.05
		5 – Used	0.78	0.02	0.74	0.01	8.39	0.03	7.99	0.07
	5	1 – New	28.74	0.96	26.43	0.92	22.64	0.35	20.03	0.13
		1 – Used	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		2 – New	9.36	0.53	8.60	0.46	20.14	0.18	18.64	0.12
		2 – Used	20.03	0.39	18.19	0.33	22.57	0.12	20.31	0.02
		5 – New	1.44	0.02	1.36	0.02	19.58	0.12	18.49	0.11

		5 – Used	2.44	0.03	2.29	0.02	21.09	0.06	19.83	0.04
LD 45	1	1 – New	0.43	0.01	0.42	0.01	4.90	0.02	4.69	0.03
		1 – Used	0.50	0.01	0.48	0.01	5.09	0.02	4.86	0.04
		2 – New	0.26	0.00	0.26	0.00	4.88	0.03	4.69	0.01
		2 – Used	0.28	0.01	0.28	0.00	5.10	0.02	4.88	0.02
		5 – New	0.19	0.00	0.20	0.01	5.08	0.02	4.87	0.06
		5 – Used	0.19	0.00	0.19	0.00	5.28	0.07	5.10	0.06
	2	1 – New	3.30	0.13	3.09	0.13	9.59	0.02	9.06	0.04
		1 – Used	4.33	0.16	4.04	0.15	9.94	0.06	9.30	0.01
		2 – New	0.92	0.02	0.88	0.02	9.56	0.02	9.10	0.02
		2 – Used	1.17	0.06	1.11	0.05	9.96	0.07	9.43	0.05
		5 – New	0.35	0.01	0.34	0.01	9.65	0.05	9.18	0.08
		5 –	0.40	0.01	0.39	0.01	10.04	0.07	9.57	0.05

		Used								
	5	1 – New	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		1 – Used	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		2 – New	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		2 – Used	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		5 – New	5.70	0.54	5.25	0.48	23.61	0.33	21.93	0.18
		5 – Used	8.23	0.35	7.53	0.30	24.36	0.10	22.48	0.08