STRENGTHENING CLOTHING DAMAGE ANALYSIS:

QUANTIFICATION OF STABBING FORCE AND WEATHERING

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Copyright Statement

Abstract

Clothing damage analysis is a forensic discipline which provides mainly qualitative evidential value to criminal cases. This two-part investigation strengthens the value of clothing damage analysis through both quantitative and qualitative assessment. The aim of the first study was to determine whether the direction of a weapon (n=6) has any influence on the force required to penetrate a 50:50 polyester/cotton blend fabric. This was carried out at 2 speeds - 100mm/min and 2000mm/min - in a controlled manner using a universal strength tester. Only 2 weapons displayed any distinct differences in forces between some, but not all directions. The variability and overlap of results dictates that caution must be exercised when reporting on the force required to stab fabric. The cut lengths were examined to determine whether stab cuts lengths reflected the weapon width. The cuts were always smaller than the blade width and the bias cuts were always smaller than those in the warp and weft; this was due to the natural stretch which is more pronounced in the bias. The aim of the second study was to discover the evidential value of clothing damage after weathering. Stab cuts were created by different knives (n=2) into the same fabric draped over polystyrene, in the warp and bias directions. The samples were mounted and placed outside for periods of 1, 4 and 8 weeks. The damage was analysed through measurements of the cuts (quantitative), and the identity of the weapon was determined through the cut morphology (qualitative). The stab cuts lengths changed progressively through time, more so in the bias than the warp, but the weapon types remained identifiable. This outcome suggests that the evidential value of clothing after outdoor weathering remains high.

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Contents

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Glossary of terms

Forensic – relating to or denoting the application of scientific methods and techniques to the investigation of crime, and relating to courts of law

Force – a physical influence exerted by one body on another which produces acceleration of bodies that are free to move and deformation of bodies that are not free to move

Weapon – a thing designed or used for inflicting bodily harm or physical damage

Qualitative – measuring by the quality of something rather than its quantity

Quantitative – measuring by the quantity of something rather than its quality

Fibre – a thread or filament from which a textile is formed

Yarn – spun thread used for knitting, weaving or sewing

Weave - form fabric by interlacing long threads passing in one direction with others at a right angle to them

Warp – in weaving, the threads on a loom over and under which other threads (the weft) are passed to make cloth

Weft – in weaving, the crosswise threads on a loom that are passed over and under the warp threads to make cloth

Bias – a direction diagonal to the weave of a fabric

Selvedge – an edged formed during the production of cloth that will not fray

Tensile strength – the strength of a material under tension

Chapter 1: Introduction

Textiles are ubiquitous in our lives and so when a serious crime has taken place, they are frequently present and can therefore potentially provide evidential value to a criminal case [1-11].

In their most basic form, textiles are fibres of natural, synthetic or semi-synthetic origin. Natural fibres are harvested either from plants or animals and are normally readily biodegradable, although evidence of early woollen textile remains have been found in Egypt from 3-4000BC [93]. Plants yield a variety of natural fibres which are versatile in their end use. Long, robust fibres such as coconut taken from the fruit of the plant, and straw taken from the stem of plants can be woven into items such as baskets and hats. Cotton originates from the seed of the plant and is seen in many modern textiles such a clothing, bedding and upholstery. Synthetic fibres such as polyester, nylon and acrylic are formed by extruding a polymer into either water or air to form a continuous filament. Rayon is classed as semi-synthetic as it is produced in a similar manner to synthetic fibres, but the polymer-type substance is created from natural wood pulp. Natural fibres such as cotton and wool were the first type of fibres used for clothing until the 1940s when synthetic fibres were introduced. The late 20th century saw synthetics dominating with 65% of the market. Many modern day fabrics are manufactured using a combination of fibre types to achieve optimum performance, [80] cost, durability and end use.

To produce woven or knitted fabric, short fibres are aligned through carding and then spun to form yarns. These yarns are twisted together to form S or Z twist yarns (the direction of the twist) which can then be used for knitting or weaving [94]. In weaving, the warp yarns along the length of a loom originate from a warp beam; weft yarns are passed over and under these warp threads, resulting in a woven fabric (figure 1). The bias describes the direction diagonal to the weave of the fabric. Other textiles are available in the form of netting, plaiting [94] and felting (wool only).

Figure 1: A weaving loom demonstrating the warp and weft directions [95].

The forensic discipline of clothing damage analysis can be used to support or refute a particular hypothesis [7]. It must be determined whether the damage has been created naturally through wear and tear [6, 7, 12] or deliberately in a false allegation case [1, 2]. Ideally, the examiner should be informed of any clothing damage created by medical staff during removal of garments for access [13]. When clothing or other associated textiles are damaged, examination may reveal the type of weapon and the manner in which it was used [6]. The presence of damaged clothing is particularly useful when the body is absent, or decomposed to such an extent that the body provides no evidence as to the contributing factors to their demise [5].

The term homicide is used throughout to describe offenses of murder, manslaughter, infanticide and corporate manslaughter as recorded by the British police [14], and does not include suicide. It may be considered that the lack of clothing damage indicates suicide as opposed to homicide. Edirisinghe & Busuttil believe that a person taking their own life is more likely to move or remove their clothing from the area to be cut or stabbed [15]. Conversely, a study of suicides by sharp weapon injury by Fukube *et al.* was carried out by an investigation of inquest records. The authors found that of the 28 cases where cuts or stabs were to the trunk, clothing damage was present in 11 (39%) cases. Even though in the majority of cases of these suicides clothing damage was absent (61%), the authors conclude that ‘clothing damage does not indicate homicide’ [16]. Further studies of homicide inquest records would contribute to this argument, with particular focus on whether clothing damage is ever absent.

1.1 Analysing clothing damage

Prior to 2008, the Government consulted the Forensic Science Service Ltd. for advice on any forensic issues. In 2008, the Home Secretary appointed Andrew Rennison as the Forensic Science Regulator, whose main role would be to 'set and maintain quality standards for the use of forensic science for the Criminal Justice System in England and Wales.' The aim was for the public and courts to gain confidence in the reliability of forensic evidence [18]. The 'Codes of Practice and Conduct' document has since been devised which states that every forensic laboratory must be assessed against BS EN ISO/IEC 17025:2005 [19] to achieve accreditation by UKAS - The United Kingdom Accreditation Service. The document contains a detailed list of types of laboratory activity such as processing biological samples; blood pattern analysis; fingermarks; toolmarks; firearms; footwear marks impression comparison, drug analysis and digital data recovery each with a corresponding code of conduct commencement date. As clothing damage analysis is not specified in this list, the code of conduct for the forensic laboratories own procedures is covered under the generic heading 'Laboratory activity including, but not limited to, handling, developing, analysing and/or interpreting scientific evidence not listed separately here.'

Even though there has been an attempt to improve standards within forensic science, it remains that there are no specific standard operating procedures for assessing clothing damage. This is in stark contrast to the textile industry. For many years now, it has been a requirement for cloth manufacturers to test their product in accordance with standards specified by the customer, for example ASTM, ISO, M&S, NEXT, adidas and British Standards. Testing can include a range of colour fastness tests; abrasion; compression and puncture; drape; flammability; pilling, tear strength etc. [20]. These established standards and procedures are performed by annually accredited technicians, with some tests taking place in an atmospherically controlled environment. The results are therefore reliable and reported with confidence by the manufacturers to the customers. Few forensic researchers have incorporated such standards into their work. American, European and British Standards were incorporated into this research wherever possible.

Clothing damage analysis remains a highly subjective field. In 2006, a study by Boland *et al.* [17] highlighted the need for a systematic approach within the discipline and suggested the creation of standard operating procedures. The goal was to create a system that would lead to a less subjective interpretation of clothing damage; the discipline would therefore become a 'robust subjective technique' just as fingerprint identification, histological semen identification and footwear mark identification were thought to be around that time.

Subsequently, the robustness of some forensic science disciplines was challenged in a report from the National Research Council in 2009. Amongst others, toolmark analysis came under scrutiny, which has relevance to this thesis. At present, the toolmark analyst makes subjective qualitative judgements of the individual, class and subclass characteristics of the damage, and the marks are then compared with the suspect tool. Training programmes have been introduced by the Association of Firearm and Toolmark Examiners (AFTE) with the aim to broaden the knowledge of the examiner, but the report reiterates that no specific protocol has been developed and that current guidelines do not consider the source of bias, variability, repeatability, reliability or the number of correlations required. The report recommends that toolmark analysis, as all methods of forensic science, does not require an approach as objective as DNA analysis, but should have a 'precisely specified, scientifically justified series of steps that lead to results with well characterized confidence limits' [96]. Subjectivity remains an essential and valuable skill integral to some forensic disciplines, but increased objectivity may contribute to a more convincing conclusion where subjectivity cannot be eradicated. This thesis includes a more objective approach through the inclusion of established textile testing methods together with measurements to support subjective judgements.

The closest that forensic practitioners have to laboratory guidelines is a publication from Taupin & Cwiklik (2011) entitled 'Scientific Protocols for Forensic Examination of Clothing.' The authors [21] draw upon many years of experience of carrying out simulation experiments to help solve cases [5] [6] [10]. The book contains descriptions and images of many common types of clothing damage. It must be noted that some coverage is vague (entomology, decomposition, chemical damage) and some types do not appear at all (blunt force impact, crossbows, weathering). The authors suggest, as Boland did five years previously, that there is still a need to develop clothing damage analysis procedures. They recommend a method which begins with the forensic practitioner widening their own knowledge by familiarising themselves with test damage characteristics by studying previous research. To gain maximum information from the damage, they recommend that the examiner makes objective descriptions at the fabric, yarn and fibre level, and carries out simulation experiments. The use of microscopy is not encouraged for every type of damage; the reasons behind this will become apparent throughout and will be discussed under the main type of damage.

The first assessment of any garment damage must begin with determining whether the damage is recent and forensically relevant or created naturally through normal wear and tear [6, 7, 12]. Secondly, clothing damage that has been falsified must be identified. An experiment was carried out by Daly *et al.* to distinguish between damage to a bra during a possible struggle and deliberate manipulation of the bra hooks [1]. Attempts were made to forcibly remove newly purchased bras from colleagues to determine whether similar damage to the hook and eye fastening could be replicated; only 2 new bras were used which is only a very small sample. Four different instruments were used in an attempt to reconstruct manipulation damage on 4 previously worn bras. It was concluded that scissors were used in the forensic case and this was repeated once more on a new bra. Throughout this paper, neither the brands nor the age of the bras were considered, yet bras degrade over time with regards to the fabric, stitching and fastenings, and the quality of fabric and manufacturing differs between brands. Considering all of these factors, each bra will respond to scenarios differently. Only 2 attempts were made to remove a (new) bra, yet 5 attempts were made to determine which tool could have made the damage.

Most of these issues were addressed by Williams and Haider [2] in their study of genuine or falsified damage to a bra in another alleged sexual assault case. In this case, the investigation was to determine whether a bra could be damaged by separation of the cups through forced removal and without damage to the hook and eye fastenings. The brand and size of the case bra was unidentifiable as the tag had been previously removed. As the authors recognised that the brand information was important, 9 new bras with differing brands but of similar sizes were explored. With the sample size being much healthier in this study, it allowed for a more thorough investigation; volunteers wore the bras in sitting, lying or standing positions for scenario reconstructions. Only 1 bra received damage to the fastening, and of the remaining 8, 5 were separated by the cups, 1 had a partial tear and 2 remained undamaged. Even though the extent of wear and tear on the case bra could not be determined and replicated, the outcome from using all new bras yielded results which successfully contradicted the presumptions of the defence.

The presence of abrasion through laundering and wear was used to clear a suspect who was accused of shoplifting underpants [3]. On first examination, the underpants worn by the suspect appeared to be the ones missing from a multipack. Booth & Lott used laser examination and biological staining was discovered, indicating that the underpants were not new. Microscopic examination supported this conclusion by detecting that some fibres had broken within the threads, indicating abrasion. The authors state that the presence of lint would support this conclusion further but do not reveal if this is what they found.

1.2 Types of damage

There are many causes of damage to clothing resulting in different types. Damage can appear in isolation but often there is more than one type present [13], therefore the types of damage are loosely grouped into the following categories to aid discussion: mechanical, chemical, heat and environmental damage.

1.2.1 Mechanical damage

Mechanical damage occurs when the fabric comes into contact with another object resulting in abrasion, tearing, blunt force impact, cuts (slash, scissor and stab) and punctures including firearms. This category provides the highest volume of forensic casework within clothing damage [13] and this is reflected by the proportion of studies in this review. To illustrate, a total of 25,933 offences involving a knife or a sharp implement were recorded by the police in England and Wales in the year ending September 2013 [14]. Stabbing is the most common form of homicide in the UK with the majority of stab wounds inflicted on the trunk of the victim [35]. The most common type of weapon used in stabbings is the kitchen knife [33] possibly due to being readily available and accessible [34]. Other weapons used in serious crime reflect availability, for example a gardening knife called the parang is commonly used in homicides in Malaysia [36]. Glass accounted for 6.5% of weapons used in stabbing assaults in England and Wales in 2008 [33], and in Scotland, a study of male young offenders revealed that glass was the second most common weapon used in assaults, usually occurring after the consumption of off-trade alcohol from glass containers. These crimes were not premeditated and so the study highlighted the ease in which a glass container had become a weapon [37].

Many forensic researchers have chosen to use these skin simulants in their experiments when investigating mechanical damage: cadavers [56] [57] [58]; corrugated pasteboard covered with carbon paper [11]; polyurethane, compliant foam and ballistic soap [22]; polyether open-cell foam [23]; silicone, closed cell polyethylene foam and open cell foam [24]; open cell polyether foam and silicone rubber [25, 26]; 10% 250 bloom gelatine [27]; pork flesh [4, 10, 12, 28]; pork flesh and silicone rubber-foam blocks [30], polyurethane over porcine skin [31], and synthetic chamois over porcine skin [29]. Understanding the performance of a skin simulant is vital if it is to be considered for forensic testing.

In an investigation by Carr *et al*. into skin simulants [62], much variability was apparent. The aim was to identify a suitable backing for fabric which could create reproducible test results. Pork shoulder was compared with 20% gelatine and expanded polystyrene (EPS). The authors concluded that EPS was the most reliable material for reproducible results, but advised that it does not respond as human tissue would. This would be of no use when measuring stab force performance but proved ideal in this current research for creating stab cuts for weathering.

As it is not proven that any one form of backing mimics the human flesh adequately, a decision was made early in this research not to back the fabric in any way. By removing this variable it allowed for exploration of how the force of the weapon is affected by the fabric weave whilst remaining unhindered by an area of forensic science which itself requires further research. Until now, there have been no forensic studies of fabric performance in isolation whilst investigating stabbing force. These results are not intended for the reporting of standalone force data and but are for comparative purposes only within this study. These results also provide baseline data where other variables such as backings may be added at a later date for further comparison.

1.2.1.1 Stabbing force

Stab cuts and punctures are presented here together as the 2 terms are often used interchangeably. A stab cut describes the effect of any sharp instrument (e.g. a knife or glass) created in a stabbing motion, and a puncture is created with a blunter instrument, such as a screwdriver. The main area of research for stabbing and punctures is quantification of force needed to inflict the damage. The force can be described as a physical influence exerted by one body on another which produces acceleration of bodies that are free to move and deformation of bodies that are not free to move [97]. It is expected by some authors that less force is necessary to penetrate as the speed increases [56] [57] due to inertial effects [22]; this is investigated here by carrying out identical tests at 2 speeds.

When searching for stabbing force literature involving fabric, body armour resistance testing is salient [50-55], but there is also a necessity to test the stab force required to penetrate everyday clothes as it is often asked in courts what would have been the force involved in the stabbing [22, 23, 27, 30, 56-58]. Being able to quantify the answer to this question would be of benefit to the expert witness, as they are then able to reply with an informed response [30].

The origins of stab force research lie in the 1970s where Knight [56] administered stab cuts to unclothed cadavers. The knives were mounted inside a spring loaded perspex box and the force was measured via the scale in kilograms on the outside. Knight found that with a very sharp and pointed knife, penetration of the abdomen could occur with a little as 0.5Kg (4.9N) of pressure. Once the skin had been penetrated, no further force was required to cut into underlying soft tissue. Knight discovered that the amount of force required to penetrate the skin was dependent upon the sharpness at the tip of the knife, and that when the knife became blunt, the force had to be increased. The velocity at impact was recognised as important, but less so than the sharpness at the tip. Whereas the results were ground-breaking at the time and formed the basis for further studies that followed, there was an assumption that cadaveric tissue performs in the same manner as living tissue.

Three years later, Green [57] experimented with a range of knives mounted in a 'spring recorder,' similar to the equipment used by Knight. The cadaver was manually stabbed on a force platform linked to an oscilloscope, which produced graphical records. Stabs were made at contact and from 15cm away with 3 different categories of knives – short rigid sharp knives, large rigid knives and kitchen knives. The findings supported those by Knight – that it is possible to pierce the skin of a cadaver with a small amount of force, and that sharpness is more important than momentum. The graphs showed the initial maximum peak followed by the smaller peaks as the knife continued to penetrate internal tissue. Further tests were carried out on clothed cadavers wearing an aertex vest, a light shirt, woollen jumper and sports jacket; these were also stabbed at contact and at 15cm with a variety of knives. Many of the large knives and kitchen knives failed to penetrate the clothing, and some broke or bent. It was recognised that more thrust was required for easier penetration of a clothed cadaver: short rigid sharp knives at contact required an excess of 15kg (147.1N), but from 15cm away, penetration was achieved between 7kg (68.6N) and 10kg (98.1N). The minimum force required to penetrate a clothed cadaver was 4kg (39N) of pressure from 15cm with the use of a small sharp pointed chef's knife with a serrated edge. The full results were not published, only key points and so it remains unclear just how many stabs were carried out for each knife, and how many knives were used. As the stabs were made manually, the speed and angle of each stab may have differed. Layered garments were used, which reflects only one particular scenario. Any variation between results may be due to seams, buttons, tightness of the fabric, the speed of the knife, the direction of the knife to fabric warp and differing underlying cadaveric tissues as a backing, which was not accounted for in this study.

O'Callaghan used unclothed human cadaveric tissue and amputated body parts to quantify the penetrating force of a knife [58]. Sample size, mean force and force range results were given. As no details were offered about the blade, the stabbing forces are only valid for comparison purposes only for the results created. It was discovered that skin, fat and muscle together offered the most resistance at a mean of 49.5N (5kg). The next resistant was muscle at a mean of only 37.5N (3.8kg), then fat and muscle with a mean of 35N (3.7kg), with fat only being the least resistant at a mean of 2.0N (0.2kg). Unfortunately, stab cuts made to clothing covering human tissue was not explored. Again, there is an assumption that cadaveric tissue performs in the same manner as living tissue.

The importance of knife dimensions in stabbing research was investigated by Hainsworth *et al.* [23]. Knives with a range of thickness, angles and tip radii were dropped onto polyether open cell foam and the penetration depth was measured. Although only 3 tests were carried out for each knife, the authors concluded that the following affect penetrability: tip radius size; blade thickness, edge sharpness and blade geometry (shape at the tip, the taper of the blade and the cross sectional area). McCarthy *et al.* [59] agreed with this research but stressed that the tip radius was the most influential factor.

Parmar *et al*. investigated the stabbing force of blunter instruments such as screwdrivers, pens, and chisels to penetrate body analogues of silicone rubber foam and pork flesh [30]. A correlation was discovered between the cross section of the weapons and the force required to penetrate; over 100N (10.2Kg) was achieved for large screwdrivers, although there was more scattering of data for the cross head screwdrivers. Even though the number of tests were adequate according to British Standards (n=5), more tests may have revealed a different pattern of results. Unfortunately the effect of textiles was not considered.

Glass when broken can produce both sharp and blunt weapons. The force required for broken glass bottles to puncture a skin simulant of open polyether foam and silicone rubber was examined by Nolan et al. [25]. The authors achieved a range of forces from 9.8N (1Kg) to 56.7N (5.8Kg), but do not disclose the speed at which the experiments took place; this is an important factor when exploring forces. The effect of textiles was not explored.

Only a small number of studies have considered the presence of clothing when exploring the force required when creating a stabbing injury into a skin simulant (table 1). Kemp *et al.* [24] devised an experiment to compare human participant trials (HPT) with an impact rig by using 3 weapons mounted into an instrumented handle: a hunting blade, a kitchen blade and a screwdriver, and 2 fabrics. The authors were thorough and used existing textile testing methods for sample preparation: they were then degraded by laundering to 3 stages: 0, 6 and 60 cycles and then were conditioned in a standard testing atmosphere prior and post testing. The samples were mounted on a skin simulant consisting of 1.5mm layer of silicone, 30mm block of closed cell polyethylene foam and a 150mm block of open cell foam. Direction was considered – the weapon was aligned with the warp of woven fabric or the wale (vertical row of knitted loops) of knitted cloth, but there were no further tests. It is not clear how the samples were mounted or how taut they were. The results showed that the kitchen knife required the least force to penetrate at 136.3±54.8 N (13.9Kg), followed by the hunting blade at 179.1±72.5 N (18.3Kg) and then the screwdriver at 338.8±53.7 N (34.5Kg). The authors do not comment on the overlap results from the kitchen knife and hunting blade. These test results reflect the force required to stab the backing and fabric combined, and do not explore the effect of the fabric.

Aming & Chitaree used a 4" blade attached to a blade censor to measure the force of 2 stabbing actions [27]. No other knife dimensions were offered. The authors considered an underarm motion as the contact range and the overarm stabbing motion was the long range. Ten human subjects were required to stab 10% 250 bloom gelatine covered in 'cotton and jean.' The precise blend and weave knit were not given, nor the tautness of the samples or the speed or direction of the cut. The mean force for the contact range was 10N (1Kg) and 50N (5.1Kg) for the overarm long range. The ranges of results were not published and therefore their reliability is uncertain. The angle of the blade to the fabric warp may have differed each time due to the test being carried out by human participants. The authors carried out SEM analysis and suggest that the appearance of the clothing damage can indicate the degree of force used. They acknowledge that further investigation with different textiles is necessary, but do not consider weapon properties.

The effect that clothing had on the force necessary to stab a skin simulant consisting of foam and silicone rubber was investigated by Nolan *et al.* [26]. Three knives were tested 3 times on each set of clothing in no particular direction - this is a very small representative sample. The clothing was donated; this would cause problems for repeatability due to lack of knowledge around laundering and wear and tear. Most importantly, the speed in which the stab cut were applied was not offered, although speed is considered an important factor and the average forces were given without statistical analysis. It was concluded that the force varied with each item for each knife. The resultant stab cuts were examined regarding their orientation. Three stab cuts had occurred in jeans in the bias with one knife, which produced a range of 3 Newtons. Also a shirt was stabbed twice in the weft direction and once in the bias. From only 6 stab cuts, the authors concluded that yarn and weave affects force variations. Results from all the tests were not available for the reader to examine, but instead, generalisations were made. They did discover that fabric affects the force when stabbing into (backed) fabric and agree with previous research that states the tip radius is the most important factor when examining stabbing force.

A more statistical approach was taken by Annaidh *et al.* [31] when attempting to quantify the stabbing forces on polyurethane, human skin and porcine skin at a range of speeds from 100mm/min to 9.2 m/s. A range of weapons were studied: closed scissors, a flat headed screwdriver, a Phillips screwdriver, a cook's knife, a carving knife and a utility knife. They discovered that non-bladed implements require more than 300% more force than blades and that the speed had a significant effect on the force. In a second experiment, various layers of clothing were added to the polyurethane and then stabbed at 100mm/min. The number of tests for the clothing experiments was not disclosed and it is not clear which weapon was used. The tests revealed that cotton required a 10% increase in force to penetrate, and denim needed 50%. Layers were tested which showed an accumulative effect, but the direction of the weapon in relation to the weave of the fabric was not considered.

Author	Skin / simulant as reported	Fabric: composition / construction	Mean forces as reported (N)	No. of tests	Speed	Direction	Tautness
[57]	Cadaver	Aertex vest, shirt, woollen jumper & sports jacket	≥147.1 at contact – short knife	?	More thrust = easier penetration	?	?
			39-98.1 – 15cm away				
[24]	1.5mm silicone, 30mm closed cell foam & 150mm open cell foam	Cotton: 100% / bull drill & cotton:100% / single jersey plus laundering	136.3±54.8 - kitchen knife	10 males: 1 stab per permutation (n=18)	?	Mounted in warp or wale	?
			179.1±72.5 - hunting knife				
			338.8±53.7 - screwdriver				
			(No discussion of overlapping results)				
[27]	10% 250 bloom gelatine	Cotton ? / ?	10 - contact range 4" knife	10 females: 1 stab per permutation (n=2)	?	?	?
		Jean ? / ?	50 - overarm long range 4" knife				
[26]	Open cell foam, silicon rubber & polyether foam	8 types of worn clothing with composition and description	17.83 - kitchen knife in t-shirt	3 stabs on each set of pre-worn clothing with 3 knives	?	? then 3 cuts	?
			27.19 - kitchen knife in jacket				
			23.19 - combined				
[31]	2mm Polyurethane	cotton: ? / ?	PU +10% with cotton	(n=?) with ? weapons	100mm/ min	?	Biaxial tension device
		tracksuit: ? / ?	In a graphical summary				
		fleece: ? / ?	In a graphical summary				
		denim: ? / ?	PU +50% with denim				
		Denim & cotton: ? / ?	In a graphical summary				
		Fleece & cotton: ? / ?	In a graphical summary				

Table 1: A summary of previous stab force research involving clothing. This highlights the variation in approach between authors, and which variables were not considered during experimentation.

1.2.1.2 Weapon identification

Research to determine weapon identification was carried out by Costello and Lawson who compared blade dimensions and stab cut length in clothing [4]. The research arose due to a court case where a suspected murder weapon was wider than the stab cut in the shirt. It was suggested that this was due to the fabric being stretched. During testing, second hand clothing was draped or stretched over pork, and stabbed manually in the warp, weft and bias directions. The tautness was not standardised and the use of second hand clothing for comparison purposes is undesirable due to differential wear and tear across the garment. The number of stab cuts that were created for each set of parameters (knife, tautness, fabric, direction) differed greatly, ranging from 1 (twice), to 18 (once). The stab cut lengths were expressed as a percentage of the blade width (measured in situ) and the cuts were found to range from 25% (jersey fabric stretched, vegetable knife) to 148% (draped knit shirt, boning knife). Stab cuts were then created in 3 layers of clothing with 3 knives. These cut lengths did not display any particular pattern that the authors recognised. It was evident that every cut length was smaller than the blade width, whereas some of these fabrics in single layers had stab cuts larger than the knife width – this was not recognised by the authors. It was concluded that in single layers, the stab cuts shapes occurred unpredictably and the direction had no effect. Also, they state that the majority of cut lengths were less than the blade width and those that were bigger were made by the boning knife. The authors suggest that the larger cuts occurred due the knife being blunt and it was pulled the fabric into the cut, although they comment that when this was observed, the cut was not always bigger. This current research complements the work of Costello and Lawson through further investigation into the causes of the variation of stab cuts lengths in comparison with the maximum blade width. This was made possible by the creation of stab cuts in a more controlled manner.

A study was undertaken by Monahan & Harding [12] to determine whether a tear, cut, slash and stab (sharp and blunt) could be distinguished from one another and whether the weapon could be identified. The authors also investigated the effects of bleeding, wearing for 1 day, and washing in a machine then drying in a tumble dryer. A range of eleven easily accessible weapons were chosen and a variety of 4 fabrics. The clothing damage was created by placing over pork, and then the stabbing and slashing took place along the warp and weft directions; the damage was examined with a microscope at X50 magnification. The authors conclude that there are certain damage characteristics which indicate the type of weapon, but certain conditions make identification more difficult. They stress the importance of test cuts with the suspected weapon in the original garment wherever possible. The approach attempts to clearly differentiate between weapons, but does not try to prove that similar damage can be made by different implements i.e. glass and a blunt knife.

Dann *et al*. investigated the tearing behaviour of knicker fabrics, the effect laundering and the appearance of the damage was carried out [38]. The authors were thorough and used established British Standards or ISO methods for the following: sampling (n=5); domestic washing and drying procedures; mass per unit area; thickness, stitches per 10mm and tear procedures, and the samples were conditioned in a standard testing atmosphere for testing. The knicker fabrics were chosen for their similar appearance but with different properties regarding fibre content, mass, thickness and number of stitches per mm. These commonly used fabrics were laundered to 3 levels for comparison; all became weaker after laundering. The authors declare that testing fabric will differ to garment testing, but stress the necessity for understanding fabric performance in order to interpret evidence. This consistent approach revealed conflicting findings to an earlier study by Monahan & Harding [12] by the discovery that more tear permutations were possible than previously believed. Unfortunately, as the samples were not torn from the edge of a garment, this does not reflect a real scenario; the tearing behaviour may be affected by the presence of the edge seam.

The kitchen knife and crosshead screwdriver samples from the previous research from Kemp et al [24] were then subjected to further wash cycle in a unique experiment for determining the effects of laundering on stab cuts [61]. Wells *et al.* analysed the samples before and after laundering both visually and quantifiably through 10 individuals who were looking for a change in dimension, openness, fraying and definition. It was concluded that laundering alters the severance morphology of the cut sufficiently enough to make weapon identification more difficult, or even impossible. Unfortunately, the visual assessment card that the participants filled in were labelled with which knife they were looking at – a more appropriate approach might have involved testing the participant’s ability to first match the weapon with the damage.

Stowell & Card used scanning electron microscopy micrographs as a tool to differentiate between cuts and tears in a nylon fabric nightgown in an investigation of a sexual assault case [9]. A knife was alleged to have been used to cut the night gown in two, but as the knife was unavailable, the authors created experimental damage with a new scalpel, scissors and by tearing. A total of 67 fibre ends were examined for the 3 experimental damage types. The authors conclude that the damage types were identifiable by the different fibre ends. Upon closer inspection, both tearing and scalpel damage was produced which matched the bulbous features of the original garment damage. This approach to fibre damage analysis was directly challenged by Pelton [40] after a study of 600 damaged fibre ends revealed an overlap between scissor cuts, knife cuts and torn fabric. The author states that the use of SEM evidence alone will rightly continue to be challenged and discredited by lawyers.

The importance of being able to identify a weapon through recreating clothing damage was emphasized by Sitienne *et al.* [11] after a range of weapons was submitted for testing. The authors had access to the case report and analysis of the skin wounds, but the weapon could not be identified from these alone. Clothing damage analysis revealed that the weapon was a wrench with a moving head; the stab damage was able to be recreated when the rotating head was fixed. The authors believe that their knowledge around the circumstances of the assault was essential in allowing them to reconstruct events and this led them to identifying the weapon. Whereas the outcome in this investigation was successful, the method of utilising a corrugate pasteboard as a surrogate shin could be improved for future experiments.

A study by Daied *et al.* [28] investigated whether stab cuts in clothing reflected the length of skin wounds, and the blade width. To replicate skin, pig skin with underlying subcutaneous tissue was used, over which the fabric was either draped to simulate loose clothing, or stapled with weighted edges to simulate tight clothing. A number of fabrics were chosen which had modern fibre mixtures, but it is unclear whether the fabric was woven or knitted; fabric structure alone could provide variability of results. The 4 weapons used were fixed in a device which enabled controlled applications and 20 stabs were created for each permutation. The fabric and skin cuts were always less than the maximum blade width, and when the fabric was stretched the fabric cut was always smaller than the cut in the skin. The authors report an increased difference between garment and skin when the fabric contained natural fibres, but this could be due to the type of fabric construction, which was not reported. The authors recognise the need for further research regarding different weaves, and with using different stabbing motions.

It has been proven that glass cuts may be difficult to determine as they can resemble cuts made by other implements. This was highlighted in a reconstruction experiment by Taupin [7] where both knife cuts and glass cuts from a broken bottle were recreated in a simulation experiment. It was impossible to choose between the two scenarios. Experimentation by Griffin [41] has led to an improved understanding of the typical characteristics of glass cuts in both woven and knitted fabrics with synthetic and natural fibres, caused by passing through a broken window. It was discovered that glass cuts usually appear as multiple, shallow sharp blades, although tearing is also possible due to possible broad surfaces.

Further research is required to investigate the possible morphologies of stab and slash cuts created with glass.

The frequency of slash attacks was discovered by Bleetman *et al.* [42] through a retrospective study of patient records from the Casualty department of the Glasgow Royal Infirmary between 1993 and 1996. It was discovered that the highest volume (62%) occurred in clothed areas, which indicates a need for effective clothing damage analysis of slash cuts. Incidentally, their human performance study revealed that the forces required in slash attacks were only 25% of those forces achieved in stab attacks.

A method to quantify slash cuts was devised by Bostock *et al.* [43]. A relative sharpness index (RSI) was created for determining blade sharpness using different thread types; the blades were then used for applying slash cuts to fabric. The resultant slash cut was then graded at fabric yarn and fibre level on a scale of 0 to 3. The best correlation occurred between the RSI and fray when the fibre types matched. The combination of RSI and slash categorisation provides a valid scoring system which clearly indicates varying degrees of weapon bluntness. However, consideration must be given to the other reasons that the cut has a certain appearance as yarns and fibres may loosen during wearing and handling. The authors acknowledge that this categorisation only applies to this particular fabric and that more work needs to be done. This data was created in line with either the warp or the weft; yet slashes in the bias may yield very different results visually and this categorisation system may not be applicable.

Daroux *et al*, [39] carried out investigation into the effect of laundering on blunt force impact (BFI) damage and the effect of BFI on fabric pre and post laundering. Two different cotton fabrics (bull drill and single jersey knit) in single and double layers were explored. The impact force, impulse and damage size differences were compared between new fabric and that which was laundered for 6 and 30 cycles. Laundering was found to alter the appearance of the damage but did not destroy it, and the mass and thickness increased whereas dimensional stability decreased. Fibre damage was examined with SEM, but the authors advise caution when using this method. Five samples were tested for each permutation which is in accordance with British Standard fabric sampling. These samples were conditioned before testing - this was unnecessary as the impacting was not carried out in the conditioned atmosphere and so the fabric would become unconditioned during this time.

There has been a large amount of research on the ballistic impact behaviour on protective clothing (body armour) since the development of strong fibres in the 1960s. A comprehensive literature review on ballistic impact on dry woven fabric composites cites 176 references up to 2008 [44]. Since then, articles have continued to be published relating to body armour, for example, the development of a model for the ballistic impact behaviour on multi layer fabric targets [45] and a model for fabric failure through yarn slip in woven fabric [46]. In contrast, research on ballistic impact on everyday clothing is minimal, even though the police recorded 8,135 firearms offenses in 2012/ 2013 [47]. When examining clothing from shootings, gunshot residue analysis is a more commonly used approach for estimation of shooting distance [48]; the fabric damage morphology is overlooked.

Clothing damage morphology analysis is essential when investigating a shooting particularly when weathering has removed any firearm discharge residue from the clothing, where there is no soft tissue remaining, or the bullet has not been recovered. It is assumed that fire arms fired at close range will produce cruciform or stellate tears in fabric. Alakija *et al*. [49] challenged this by creating bullet entrance damage at a range of 8 distances with 4 different fire arms into 3 commonly used natural fabrics. It was discovered that the fabric performed differentially with a .22 calibre pistol, also that a .22 calibre rifle does not produce cruciform tears at any distance. As the conclusions were drawn in some cases from only 3 fires, it is possible that this small sample was not representative of all morphology possibilities.

Principles of clothing damage analysis have also been successfully applied to two separate homicide cases where mechanical damage in the form of cut and tears were analysed in non-textile mediums of paper [8] and a wire screen [32].

1.2.2 Chemical damage

Household chemicals such as bleach will permanently degrade and discolour fabric. Knowledge of the effect on fabric may contribute to determining whether chemicals were involved in a serious assault. Sunlight promotes photochemical changes in fabric which result in a fade in colour. Understanding these effects may contribute to determining exposure time outdoors or under glass. To date there has been no published research on the alteration of clothing through chemical or photochemical means in a forensic context.

1.2.3 Heat damage

Fibre identity after thermal alteration was investigated by Was [63]. The fibres (natural and synthetic) were altered by melting, gas burning and incineration and then analysed by fourier transform infrared microspectroscopy (FT-IR), scanning electron microscopy – energy dispersive X-ray spectrometry (SEM-EDX), petrographic microscopy and X-ray diffraction (XRD). The author concludes that identification is possible through a combination of all the methods, but recognises the need for further investigation as the fibres contained no dyestuffs or treatments, unlike everyday fibres. Fibre blends were not considered at this stage, but would be necessary to reflect modern fabrics.

Vapour cloud explosions, or flashburning occurs when explosive gases become ignited. The effect of this on 41 different garments was explored by Was-Gubula & Krauss through examining changes to the morphological structure of fibres with a stereomicroscope and SEM. Different results were presented in two journals. In the first paper (Forensic Science International) the results were presented for isolated fibre types i.e.100% cotton t-shirt [64]. The second paper reported on garments consisting of fibre blends i.e. a polycotton skirt, which represents modern fabrics more accurately [65]. Both papers claim that fabric damage observed in this research is specific to vapour cloud explosions although no other forms of heat damage were evaluated for comparison.

The same authors go on to attempt to determine whether specific damage to fibres is created when made by a heating plate or an open gas flame, and again use an optical microscope and SEM [66]. The same fabrics from their previous experiment were used. The samples were weighted onto a hotplate at 350^{0}C for either 30 or 15 seconds, depending on the speed of melting or charring of the textiles. Other samples were exposed to open flame until the point of burning or melting. The authors conclude that examination of the fibres from both the hotplate and the open flame revealed differences when compared with their previous vapour cloud research, although no attempt was made to vary the exposure time to explore possible similarities between these types of heat exposure and the vapour cloud explosion.

Leung & Halliday [67] contradict Was-Gubala & Kraus by stating that there are at least 2 alternative forms of heat damage that resemble vapour cloud explosion, or flashburning; these being ironing and some heat finishing processes in cloth manufacturing. Incidentally, they report on many others causes of textile damage by heat which differ in appearance to flashburning e.g. tumble drying; hot-working, cigarette smoking related burns and from being in close proximity to a large fire. The authors are informative and report on the temperature at which common fabrics are affected by heat, and how they respond. Details are provided of 2 court cases where flashburning evidence contributed to murder convictions.

Clothing flammability was investigated by Hirschler *et al.* [68] due to the retrospective nature of product liability investigation which occurs when determining whether the clothing was at fault by being unreasonably dangerous. The authors tested 17 garments with 3 different methods; the main aims were to challenge the 1953 flammability standard still in use in the

USA, and to investigate the fire-related properties of fabrics with differing compositions. The results indicated that the methods were consistent, proving that the 'old' standard was still valid, and that ignition and flame spread rate was mainly affected by density rather than composition. The relevance of this research could have been improved with the inclusion of modern clothing such as hoodies and leggings.

1.2.4 Environmental factors

Environmental factors may cause and alter clothing damage; both must be considered when assessing clothing.

1.2.4.1 The surface environment

Normally, within the textile industry, weathering through outdoor exposure or by artificial means is carried out for testing the colourfastness of dyes. Any clothing damage carried out perimortem (around the time of death), and then exposed to the elements may become altered by the weather, yet there is very little research done in this area. This current research aims to examine the evidential value of weapon identification through clothing damage after a period of outdoor exposure.

The performances of five agrotextiles (for agricultural use) were researched by Dierickx & Berghe, regarding the effects of natural weathering over a period of 5 years. Changes to thickness, mass, tensile strength and strain at break were analysed by adopting appropriate established standards; each test was carried out in a conditioned atmosphere. This research has demonstrated that the composition of, and treatments applied to textiles have a differential affect on degradation by weathering. This information would be useful when providing scientific support in a legal context, but it also justifies the need for further research in this area [69].

Research entitled 'The Effects of Scavenging and Weathering on Fabric Damage' was carried out by Koch & Deaver [70] which explored the effects of weathering on stabbed or shot clothing on cadavers. A small amount of cuts and shots were made to new clothing; this was sent out to the Mosquito Research Laboratory, Texas, where it clothed 6 pigs. As the cuts and shots were pre-made, there were no corresponding skin wounds. In a real scenario, the corresponding wounds would attract Diptera which would oviposit (lay eggs) here and this would affect the rate of decomposition [71]. Four of the 6 pigs were inside or covered up, so only 2 were subjected to outdoor exposure, and they were exposed for different lengths of time. No control clothing was exposed to weathering and so the cause of the appearance of extra holes could not be identified from a choice of weathering, bloating, insect activity, decomposition chemistry or any other unknown factor. The weather data was not offered and so it remains unclear as to exactly what the clothed pigs endured. The authors concluded that edges of the damage became more defined and the single edged blade could still be identified by the v shaped notch made by the blade at one edge of the cut [70].

Komar & Beattie carried out a decomposition experiment in Canada with 20 clothed pigs in a variety of depositional environments [72]. Canid activity in the clothing was identified by puncture marks in a scarf, chew and puncture marks in a shirt tail and the distinct movement of clothes in one direction. It was discovered that during the bloat stage of decomposition, swelling of the abdomen caused shirt buttons to tear off and the seams to burst and then maggot masses moved clothing to below and above the carcass. These clothing patterns and damage are similar to that which is seen in sexual homicide cases. The authors suggest that the assessment of the victim, the clothing and the vicinity for the presence of insects is necessary for effective interpretation. It is possible that the insects caused further damage (holes), but this was not reported.

A study by anthropologists Steadman & Worne from the USA reports a case of domestic canine scavenging in an indoor environment. Clothing recovered from the scene was reported as being found on the floor near to the remains and 'covered with dog hair but was not shredded or otherwise compromised.' The authors assume that the clothing - sweatpants and a sweatshirt – was worn by the victim at time of death and conclude that it did not appear to be a deterrent to the dogs [73]. The authors did not considered that the victim may have been undressed at the time of death. It is not clear how the clothing was examined, but it is not unreasonable to suggest that examination by a trained clothing damage analyst may have revealed teeth marks or snags from the teeth or paws of the dogs and could have contributed towards recreating the series of events surrounding the death of the victim.

The importance of experience when assessing clothing damage caused by animals is highlighted in the case of Azaria Chamberlain, who went missing at Uluru (Ayers Rock) in 1980. Only a damaged and bloody jumpsuit was found initially, and then a matinee jacket was found much later. The damage to the clothing caused 'great conflict of expert opinion,' as to whether it was cause by a dingo. After 4 inquests, the final one being in 2012, it was determined that a dingo attack caused the child's death [74].

1.2.4.2 The burial environment

The first degradation experiment for textiles was called The Experimental Earthworks Project which was set up in the 1960s. The aim was to study the long term degradation of archaeological materials such as dyed and undyed woollen cloth, linen, flax, goatskin, sponges soaked in blood, leather and hemp and other non-textile items. The items were placed in acidic sandy soils, chalk and turf, to be excavated after 2, 4, 8, 16, 32, 64 and 128 years [75]. After 32 years, the woollen dyed fabric showed the most resistance to microbial degradation, thought to be due to the metal ions and the mordants (dye fixer) in the dye [76]. The authors Lawson *et al*. recognise that advancement in scientific techniques has meant that earlier samples have not benefitted from modern soil microbiological techniques. Unfortunately, no fabrics with synthetic fibres were deposited even though they were available.

Further to this, the effect of dyes on fabric was investigated with 2 denim fabrics and un-dyed woven cotton. Samples were placed in clandestine grave sites of garden soil, moorland and under the floor of a cellar [76]; clandestine burials occur in around 1 in every 50 murders [77]. The samples were left for 70 and 140 days, but it is unclear why these periods were chosen as details from the original research are in an unpublished master's thesis. The environments were measured for pH, moisture and organic content. Degradation was measured on the amount of recoverable material, which is of most use in a forensic context. As expected, undyed cotton degraded the most and the synthetic blue dye was most resistant [76]. Contemporary fabric blends were not investigated.

An experiment was devised by Was-Gubula & Salerno-Kochan to biodegrade fabric under known conditions. Three different coloured military woollen fabrics with anti-moth finishing which were placed in standardised biologically active soil of peat, river sand, compost and dung. The samples were kept at 28^{0}C, 60% humidity and pH 6-7, as these were optimum conditions for bacteria and fungi to thrive. The samples were examined organoleptically (with senses), with a stereomicroscope and then by SEM. The fabric decayed differentially according to dye colour. Fungus and bacteria altered the fabric colour, the weave became loose and holes formed. After 5-6 weeks the fabric had completely degraded. The authors suggest that durability tests or chemical analysis should also be carried out [78]. This experiment provides a controlled environment of optimum conditions, but a small representative sample was used – one strip was used for each permutation.

If textiles are present, their decomposition rates will be affected by the presence of a decomposing body. The effect that a cadaver has on the degradation of hair, metal and textiles was investigated by Wilson *et al.* with pigs as human analogues [79]. The textiles are reported by Janaway [80] and consisted of un-dyed wool, 3 weights of un-dyed cotton and commercial blue denim; these were buried in triplicate above and below the pig at 30cm and 60 cm depth. The pigs were placed in 3 different sites and exhumed after 6 months, 1 year and 2 years. This experiment was thorough in its method, yet more complex blends of fabrics were necessary to reflect modern clothing.

In contrast to traditional archaeological studies, an experiment by Mitchell et al [81], investigated the degradation effect of clandestine burial on modern shirting. This investigation involved 2 shirts consisting of 65:35 polyester cotton blend and 100% cotton in 3 states of laundering: unwashed and laundered both 6 and 60 times. They were buried in both sand and clay for 15 and 30 days. After this time they were placed in a standard testing atmosphere for 24 hours before being tested for mass, thickness, tear force, force to initiate tearing and work to initiate tearing. Descriptive statistics were carried out on the data. The authors concluded that both of these fabrics degraded in a short length of time, albeit variably, and suggest that understanding the variables regarding decomposition may have forensic implications when evaluating the time scale of a crime. [80]. Any reference to the weather conditions during the testing period are invalid as the data was used from a weather station 30 miles away. If degradation is to be used as a tool for assessing time scales, then it is essential that the forensic practitioner understands the conditions where textiles are preserved due to the inhibition of microbial activity in water logging, freezing and desiccation.

1.3 Aims of the research

As can be seen from the review of literature, clothing damage analysis is a forensic discipline that relies very much on the subjective judgement and personal expertise of the forensic practitioner. To be able to answer forensic questions with some precision, there is a need to explore the inclusion of more objective approaches into the discipline. The purpose of this research is to create new quantifiable data which will contribute to the forensic knowledge pool and enhance the understanding of fabric performance for those practitioners involved in clothing damage analysis. There are three main areas to be examined: how the force required to stab fabric differs according to fabric direction, weapon identity and the effects of weathering on stab cuts in fabric.

1.3.1 Force aims

The aim of the stab force experimentation is to ascertain whether the direction of the weapon with regard to the weave of a fabric has any effect on the force required to penetrate. Additionally, there will be an opportunity to examine if the direction of the stab cut has any effect on the resulting cut length.

1.3.2 Weathering aims

The first weathering aim is to determine whether the weapons may be identified through their stab cut morphology in the fabric. Any differences in the stab cuts will be identified between the blades (n=2) regarding fabric snag frequency, cut shape and cut length in the warp and bias directions.

The second aim is to justify the evidential value of clothing damage after natural weathering, by determining the extent of alteration of the severance morphology of the stab cuts, as alteration may thwart weapon identification. The extent of alteration will be examined with regards to weapon type, direction of the stab cut and the length of exposure.

Chapter 2: Materials and Methods

2.1 Materials

2.1.1 The fabric

The piece of fabric is a 50% polyester and 50% cotton blend with a 1/1 plain weave which closely resembles some modern day male shirting material, worn on the torso (figure 2). This fabric type was chosen after a study of homicide in London revealed that the majority of homicide cases involved stabbing with multiple wounds to the trunk, and the male to female ratio was 2:1 [35]. The type of clothing involved was not declared, but the choice of fabric chosen for this study is one of many contemporary fabrics currently worn by males that could have been chosen to explore. It also complements a recent degradation experiment of understanding modern fabrics [81]. Samples could not be taken directly from shirts as the warp and weft directions would have been impossible to identify. The fabric was purchased as a pale blue king size percale bed sheet with a selvedge, which is the edge of the fabric produced during its manufacture and prevents unravelling. This was essential to enable accurate directional sampling in the warp (yarns originating from a warp beam on a loom during weaving), weft (those which pass over and under the warp threads creating the fabric) and bias directions at 45^0 diagonal to the fabric weave.

This simple woven fabric was chosen to enable the creation of fundamental data before considering more complicated woven fabrics and knitted garments. The data is for comparative purposes only within this study, and is not for declaring the absolute stabbing force for this fabric in a real scenario.

Figure 2: A plain weave shirt currently available from Marks and Spencer with 55% cotton, 45% polyester composition [98].

It remained unwashed before considering adding the variable of degradation through laundering. Tests were carried out to discover necessary information about the fabric and the methods may be seen in the following section. The tests revealed that this lightweight fabric weighed in at 104g/m^2 and the thickness was measured at 0.2 mm. The threads per 10mm were counted which resulted in 30 warp ends and 25 weft picks. A tensile strength test was carried out to highlight any differences in behaviour between the warp, weft and bias directions under an established textile testing method. Table 1 displays these results along with the extension of the fabric at breaking point. The coefficients of variations were calculated to examine the variance of data for future comparisons.

Direction	**Warp**		**Weft**		**Bias**	
Sample no.	**Max Force (N)**	**Extension (mm)**	**Max Force (N)**	**Extension (mm)**	**Max Force (N)**	**Extension (mm)**
1	590.19	11.14	449.71	15.25	226.16	31.87
2	627.99	11.65	443.03	15.74	254.54	34.35
3	607.77	11.14	444.14	15.48	296.12	36.45
4	596.28	10.87	401.54	15.06	271.06	34.88
5	606.24	11.46	447.87	15.58	268.34	35.11
Mean	605.694	11.252	437.258	15.422	263.244	34.532
CV	0.023793	0.027127	0.046083	0.017462	0.097201	0.048572

Table 2: Tensile strength test, extension and coefficient of variation results in the warp, weft and bias directions for a 50% polyester / 50% cotton blend fabric.

2.1.2 The weapons

To create the stab force data, six weapons were used. Three different domestic knives were chosen - a bread knife and two single edged knives with different blade profiles (table 3: nos. 1, 2 & 3). These reflect weapons which are readily available. It was necessary to remove the handles from these 3 knives due to mounting difficulties. A double edged blade diving knife was chosen (table 3: no.4) to represent other non-domestic knives. All knives had been used prior to testing to reflect real scenarios and each of the maximum blade widths differed. As screwdrivers are also used in stabbing incidents, the stab forces of both a slotted head (table 3: no.5) and a crosshead (table 3: no. 6) screwdrivers were explored. These took the form of drill bits to enable mounting in the machinery.

For the weathering by outdoor exposure experiment and the creation of the manually applied stab cuts, 2 knives were chosen with similar blade profiles - one single edged blade and one double edged blade (table 3: nos. 3 & 4).

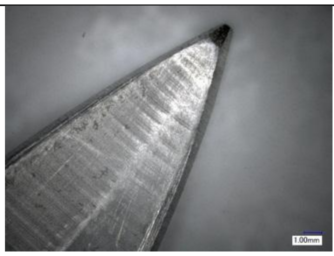
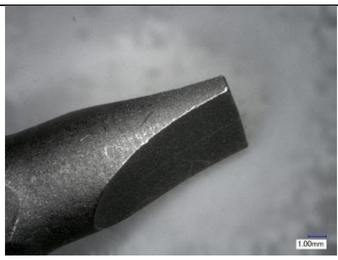
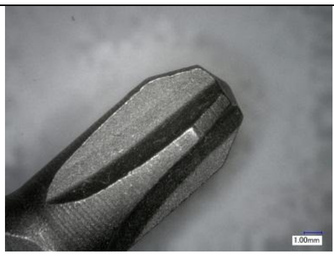
Description of weapon & maximum blade width (mm)	Image of weapon	Weapon Tip
1. Breadknife (25)		
2. Single edged blade with a straight spine (18.5)		
3. Single edged blade with a curved spine (19.5)		
4. Double edged blade (24)		
5. Slotted head screwdriver drill bit		
6. Crosshead screwdriver drill bit		

Table 3: All six weapons used in this research with maximum blade widths.

2.1.3 Stab force equipment - Titan[4]

Titan[4], a universal strength tester was used for the research into the stab force required for a variety of weapons to penetrate fabric (figure 3).

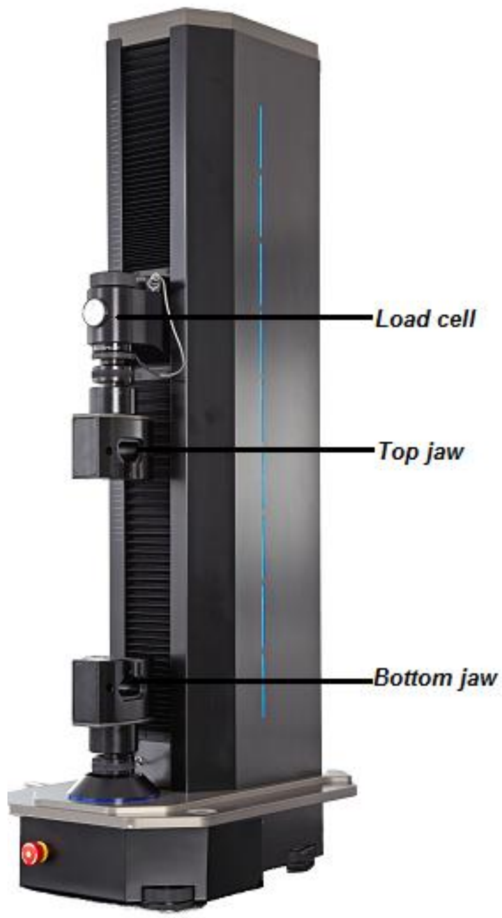


Figure 3: Titan[4] Universal Strength Tester (Image: James Heal)

The Titan[4] is an established textile testing machine designed for tension and compression tests, and is calibrated to ISO 7500-1 (UKAS accredited), ASTM E4 & ASTM D76. It is run by TestWise Test Analysis Software which is loaded with retailer's test methods and national and international standards. The standards editor allowed for the creation of the new methods for this research. Titan[4] was situated in the air conditioned laboratory at 20±2^{0}C & 65±4% relative humidity. The measuring principle of Titan[4] is the constant rate of extension (CRE). Early experimentation revealed that the most appropriate load cell for the top jaw would be 120N (+/- 0.5% accuracy) from a choice of 120N, 600N and 3000N. The top jaw has a jog speed range from 1 – 2000 mm/min (+/- 0.005% accuracy). The bottom jaw was removed and replaced with a clamp for holding the fabric sample, which provides a circular test area (figure 4).

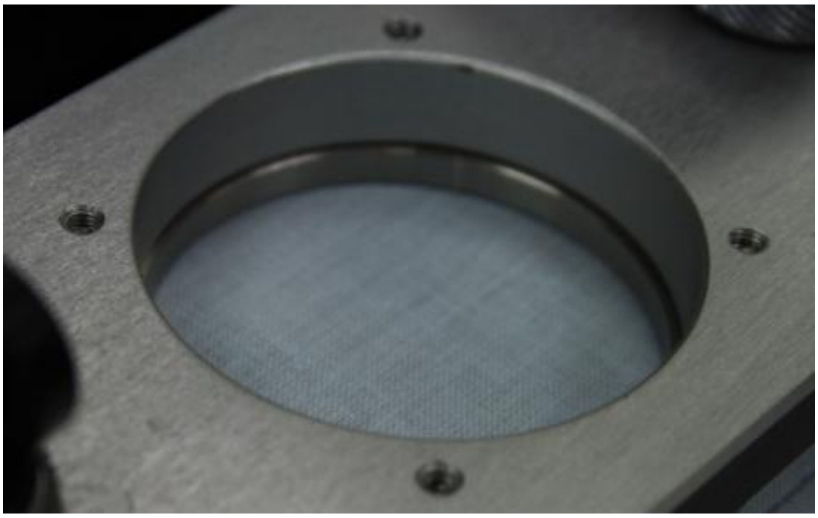


Figure 4: Mounted fabric in the bottom clamp showing circular testing area.

2.1.4 Weathering frames

Three identical wooden weathering frames were designed, cut and assembled (figure 5). The frame was nailed together and secured with tape to withstand the elements. The frame bases were approximately 55cm X 55cm with a front elevation angle of $26^{0.}$ This angle was chosen as it is in accordance with ASTM G7/G7M-11 Standard Practice for Atmospheric Environmental Exposure testing of Non-Metallic Materials [82]. Each frame accommodated 6 samples (fabric sampling will be discussed in the methods section) which were attached securely along the top dowelling rail with 75mm wide clips approximately 10mm apart. The rail was tilted to allow the samples to hang freely towards the bottom rail. The strips were then attached loosely to the bottom dowelling rail, again with 75mm wide clips. This avoided overstretching the samples but held them securely in place for the correct angle of exposure. Each sample remained un-backed as it is necessary to identify how fabric behaves without considering the performance and effect of the wide variety of different backings used within forensic testing. The samples were allowed to move freely yet they were adequately elevated from the ground to avoid soaking up static water.

Figure 5: One completed frame before outdoor exposure displaying the 26^{0} angle of elevation.

2.2 Methods

2.2.1 Fabric properties

An outline of the standard testing atmosphere and the 4 test standards to determine properties of the fabric are outlined here as they are essential the research.

2.2.1.1 Standard testing atmosphere

Each test for determining fabric properties was carried out in accordance with British Standard *BS EN ISO 139:2005+A1:2001, Textiles – Standard atmospheres for conditioning and testing* [83]. All stab force data was also created in a standard testing atmosphere. Before testing, the samples were placed in an atmosphere with a temperature of 20 ± 2^{0}C, and a relative humidity of 65±4%. The samples were positioned to allow free flowing air access, and were left until they reached equilibrium with the atmosphere. Each of the samples involved in this research were exposed to the standard testing atmosphere for at least a week (although equilibrium would have been reached much sooner). This ensured that each sample had been exposed to the same conditions for comparable testing.

2.2.1.2 Fabric weight

The fabric weight was determined by testing in accordance with British Standard *BS EN 12127:1998, Textiles - Fabrics – Determination of mass per unit area using small samples* [84]. The fabric was conditioned in a standard testing atmosphere before testing. Five samples were taken from different areas of the fabric containing different warp and weft yarns using a cutting device with an area of 100cm^2 (figure 6). The 5 samples were weighed individually and the results were calculated as follows:

$$\text{Mass g/m}^2 = \frac{\text{mass (g) test sample X 10000}}{\text{area of test specimen (cm}^{2)}}$$

The mean mass was calculated and expressed as grams per square metre to 3 significant figures.

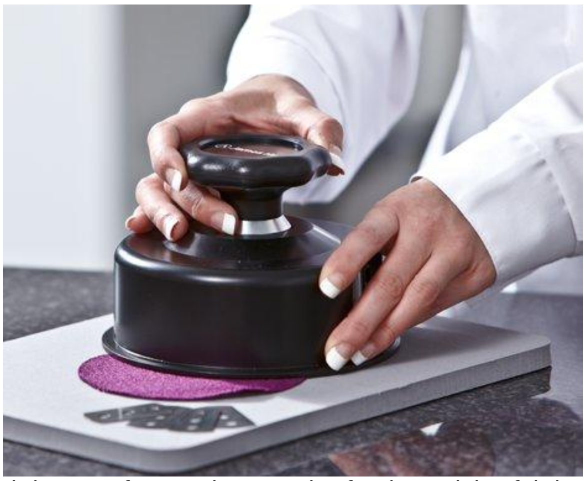


Figure 6: Fabric cutter for creating samples for determining fabric weight [85]

2.2.1.3 Fabric thickness

The fabric thickness was determined by testing in accordance with British Standard *BS EN ISO 5084:1997, Textiles – Determination of thickness of textiles and textile products* [87]. Each fabric sample was conditioned in a standard testing atmosphere before testing and then placed on the reference plate of a thickness tester (figure 7). Pressure was applied with a 50.5mm diameter presser foot at 1 +/-0.01 kPa and a reading was taken after 30+/-5 seconds. This was carried out 5 times across the samples and the average was presented with an accuracy of +/-0.01mm. Fabric thickness before and after weathering was compared.

Figure 7: Thickness tester [86]

2.2.1.4 Number of yarns per 10mm

The number of yarns per 10mm was determined in accordance with British Standard *BS ISO 4602:2010, Reinforcements – Woven fabrics – Determination of number of yarns per unit length of warp and weft (Method B – Measurement over a fixed distance)* [88]. The fabric was conditioned in a standard testing atmosphere before testing. A counting glass (figure 8) was placed on the fabric without applying excess pressure. The warp yarns were counted over a distance of 50mm. This was repeated across the fabric to give 4 readings from 4 different warp sections. The process was repeated for the weft yarns. The results were calculated using the following equation and expressed as yarns per 10mm:

$$N = \frac{\text{number of yarns counted X 10mm}}{\text{50mm}}$$

Figure 8: Counting glass [89]

2.2.1.5 Tensile strength

The tensile strength of the fabric was determined by testing in accordance with British Standard *BS EN ISO 13934-1:1999, Textiles – Tensile properties of fabrics – Part 1: Determination of maximum force and elongation maximum force using the strip method* [90]. Five samples were cut parallel to the warp and 5 parallel to the weft with each sample containing different threads as per the standard; no 2 warp samples had the same longitudinal yarns, and no weft samples shared the same picks. Each of the 10 samples was cut out at 250mm in length and 60mm wide. The width was frayed down to 50mm +/-0.5mm before conditioning in a standard testing atmosphere. Bias testing is not required by the standard, but for the purpose of this research, 5 bias samples (250mm X 50mm) were created. Once conditioned, each of the 15 samples underwent the same process. Each was mounted centrally in the jaws of Titan[4] (figure 3) set with a gauge length of 200mm +/-1mm and a pretension of 2N. The appropriate standard was activated and the jaws moved apart at a speed of 100mm/min until the fabric ruptured. The maximum force (Newtons) and extension (mm) were recorded, and the mean values and coefficients of variations were calculated.

2.2.2 Stab force methods

2.2.2.1 Stab force fabric sampling

The face of the fabric was identified by the proud holes in the selvedge which were created by the tenterhooks during processing; this was necessary as each fabric sample was tested on the face side. For each permutation, a fabric strip was cut 75mm wide and 400mm in length - this allowed for 5 tests per strip which is based on the recommended number of tests required for many British Standards for the physical testing of textiles. Other forensic researchers have chosen to use this number of samples [30] [39] [79], which was more than others [23] [26] [81] [61] [49], although it must be noted that some chose a higher number of tests [28] [69]. There were 34 samples in total: 30 were created to test 5 of the weapons at 2 speeds and in 3 directions. Four more were created to test the cross head screwdriver drill bit at the same 2 speeds but in only 2 directions; this was due to the cross shape of the tip lining up with the warp and weft simultaneously (table 4).

Weapons	Breadknife	Kitchen knife - straight spine	Double edged knife	Kitchen knife - curved spine	Slotted screwdriver drill bit	Crosshead screwdriver drill bit
Samples at a speed of 100mm/min	Warp Weft Bias	Warp Weft Bias	Warp Weft Bias	Warp Weft Bias	Warp Weft Bias	Warp Bias
Samples at a speed of 2000mm/min	Warp Weft Bias	Warp Weft Bias	Warp Weft Bias	Warp Weft Bias	Warp Weft Bias	Warp Bias

Table 4: Summary of fabric sampling for determining the stab force - each sample was stabbed 5 times.

A set of paper controls was created for each weapon at 100mm/min; these were for the creation of data in a material with no weave, for comparison with the fabric data.

2.2.2.2 Stab force testing

The top jaw was loaded with a 120N load cell and the bottom jaw was removed and replaced with the clamp. Each weapon was mounted in turn into the top jaw, perpendicular to the fabric (figure 9). Titan[4] was manipulated via computer control to set the start and end point, and safety clearance for mounting. It was necessary to establish individual parameters for each knife to accommodate the different weapon sizes. The compression programme was then altered to ignore breakage point so that the weapon would continue travelling to the end point otherwise it would have stopped after detecting a break. These settings were saved as a new programme for that particular weapon. Each fabric sample was fixed into position face up and taut in the bottom clamp.

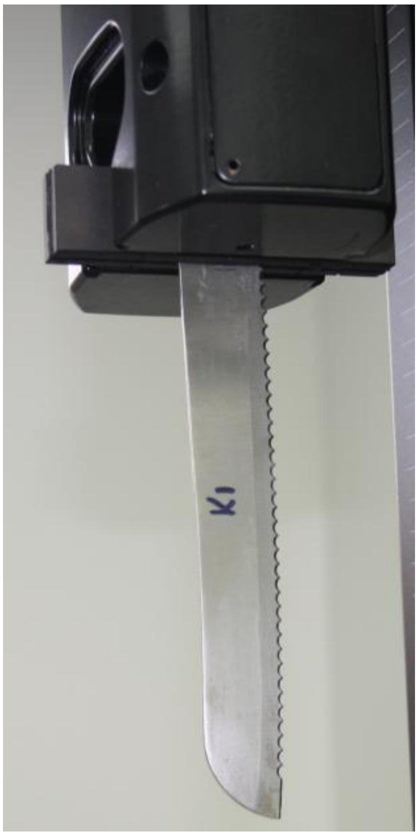


Figure 9: Breadknife mounted in the top jaw.

Once loaded and programmed, the machine was activated and the weapon descended at a controlled speed towards the fabric. Upon contact, the force registered with the software, and a graph was created showing the peak force and blade profile. The weapon stopped at the pre-programmed point after penetration of the maximum blade length and width. Data collection occurred every 50 milliseconds for each of the five stabs per permutation, and the average was calculated. Preliminary testing of the stabbing force had indicated that there would be measurable differences between directional forces, and so two speeds were chosen to explore the inertial effects on the force required to penetrate the fabric (Gilchrist 2007). After experimenting with a range of speeds (50, 100, 500, 1000, 1500 & 2000mm/min), impact velocities of 100mm/min and 2000mm/min were chosen to create a set of data for each speed, weapon and direction. The 2000mm/min speed was chosen as it is the fastest speed available for the machine, and the slower speed of 100mm/min was decided upon after assessing the preliminary results against time taken to perform the experiments; it also coincides with the tensile strength test speed.

2.2.2.3 Stab force analysis

The force profiles created by every weapon at 2 speeds were examined and compared with the weapon morphology. Comparisons were made by between the different speeds and directions for each weapon.

The mean maximum forces were reported along with the coefficient of variation for each set of results; these were examined to determine repeatability and reliability. The minimum, maximum and range of forces required to penetrate the fabric were identified from each permutation, then compared and discussed.

The stab cut lengths were calculated as a percentage of the maximum blade width and the coefficient of variation of the stab cut lengths was used to determine reliability of results. The results from each direction were also compared with the stab cut lengths in paper – a non-woven medium.

2.2.3 Methods for weathering by outdoor exposure

2.2.3.1 Fabric sampling preparation and pre-weathering analysis

A total of 18 fabric strips were created for the weathering experiment: 9 parallel to the warp, and 9 in the bias. Each strip was 75mm wide and 600mm in length – this allowed for 5 stab cuts to be created within the central 375mm of the length; the excess at each end was used for clamping onto a wooden frame. Measurement of the fabric thickness in both the warp and bias directions (3 strips each) were taken before weathering as any alteration to the stab cut may have been attributed to the shrinkage or stretching of the fabric, which may be identified by the alteration in thickness. The remaining 12 fabric strips (6 warp and 6 bias) were placed over a polystyrene block in turn and were manually stabbed, creating 5 stabs per strip (figure 10). Six of these strips (3 warp and 3 bias) were stabbed with a double edged knife, and the remaining 6 strips (3 warp and 3 bias) were stabbed with a curved spine single edged knife.

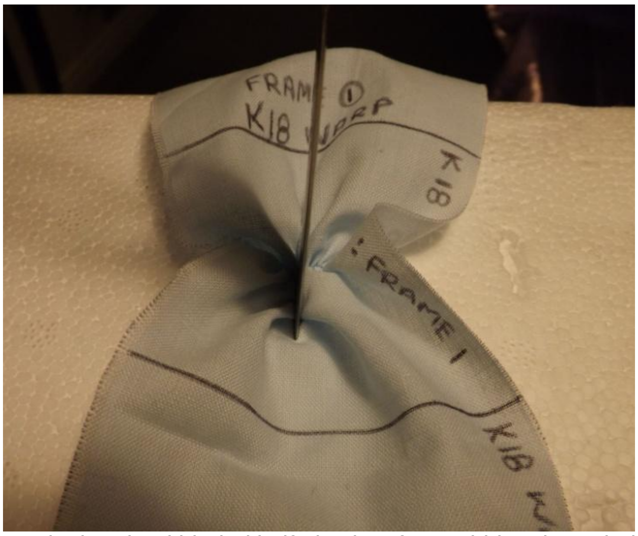


Figure 10: Single edged bladed knife in situ after stabbing through the fabric in the warp direction into a polystyrene block.

Each stab cut was examined as follows:

- any puckered cut due to a yarn snag was photographed and then straightened out leaving the yarn in situ
- photographed for comparative purposes
- it was determined whether the weapon type could be identified
- any extra damage was measured and recorded
- surface cuts were noted
- categorised according to the following shapes: straight, straight with a curved tail; curve; wave, v shape or zig-zag

Each stab cut was measured in a straight line to the nearest 0.5mm. T-test analysis was carried out on these results to identify any significant differences between the 2 directions for each blade type.

Three wooden frames were designed, assembled and loaded as described in 'materials.' Each frame held 6 samples: 1 warp and 1 bias control for thickness with no damage; 1 warp and bias sample stabbed with the double edged blade, and 1 warp and biased stabbed with the single edged blade (table 5).

	Doubled edged blade	***Curved spine single edged blade***	***Control for thickness measurement***
Frame 1: 1 week	warp / bias	warp / bias	warp / bias
Frame 2: 4 weeks	warp / bias	warp / bias	warp / bias
Frame 3: 8 weeks	warp / bias	warp / bias	warp / bias

Table 5: Summary of fabric sampling for the weathering experiment (n=18).

2.2.3.2 The procedure for weathering by outdoor exposure

The 3 loaded frames were placed outside in an allocated bay on the roof at the University of Huddersfield on Tuesday 26th February 2013, near the weather station (figure 11).

Figure 11: The weather station on the roof at the University of Huddersfield.

The frames were positioned on the roof facing due South (figure 12); this was in accordance with British Standard *BS EN ISO 105-B03:1997, Textiles – Test for colour fastness – Part B03: Colour fastness to weathering: Outdoor exposure* [91].

Figure 12: The 3 frames at the start of the weathering experiment (on 26.2.13).

All 3 frames experienced the same weather during the first week; frame 1 was retrieved after this time. Frames 2 & 3 experienced the same weather for the next 3 weeks, until frame 2 was removed after 4 weeks. Frame 3 continued being exposed for another 4 weeks and was brought inside after 8 weeks at the end of the experiment. The samples from all 3 frames were treated in the same manner after retrieval. First of all they were allowed to dry naturally inside the building before removal from the frame and their subsequent analysis.

Weather data for February, March and April 2013 was collected from the Resource Centre and Environmental Technician at the University of Huddersfield. The full weather data can be seen in appendices 44-46. A weather summary was created for the results section with the lowest and highest weekly temperatures, the average weekly rainfall and the most rain in any 12 hour period, the most prevailing wind direction and wind velocity m/s. The Beaufort scale number was added. The scale ranges from 0 (calm) to 12 (hurricane) and is based on various factors, one being the speed (m/s). A number and description was derived from the scale and then allocated to each time period for this study.

2.2.3.3 Analysis after weathering

The controls for thickness measurements were taken to the air conditioned laboratory at James Heal and left for a week before measurements were taken. Photographs were taken of each stab cut and the cuts were examined to check if the weapon type could still be identified. Any further alterations were identified and then the weathered samples were compared with the before weathering photos.

Each stab cut length was measured again in a straight line to the nearest 0.5mm. Paired sample t-test analysis was carried out to identify any statistically significant differences (where $P<0.05$) between the samples before and after weathering by outdoor exposure. These differences were analysed to identify any patterns in the results regarding knife type, stab cut direction and length of exposure.

Chapter 3: Stab force results and discussion

Investigation of the stabbing force required to puncture or stab fabric has been attempted since the 1970s, but the methods are varied. Where fabric has been included it has invariably been backed by a skin simulant, therefore comparison between the results from different studies is difficult due to the many different methods and skin simulants in use. The direction of the knife has been considered in recent research, but again a skin simulant was used in the process. Until now, there has been no research concerned with the effect the knife direction has on the stabbing force required to stab un-backed woven fabric.

Previous researchers have determined that stab cut lengths do not reflect the weapon that made them. This research seeks to identify the causes for this variation on taut samples under controlled conditions.

It must be noted that the warp direction samples are a record of the severance of the weft threads (25 per 10mm). The weft results are a record of the severance of the warp threads (30 per 10mm).

3.1 Experimental design – stab force

There are 2 hypotheses for this research. The experiment was created to determine if the force required to penetrate fabric is dependent upon the direction of the weapon in relation to the warp (the effect of the weave and thread count). The stab cut lengths were examined for any differences between directions.

The first set of objectives was to examine the weapon-force profiles in relation to the weapon and then compare the differences between the directions and speeds. The coefficients of variations (the ratio of the standard deviation to the mean) were examined; this was produced on each test report and concerns the variation of each set of maximum peak forces for each weapon in each direction at each speed. The variability and range of forces for each permutation was explored.

Secondly, the mean stab cut lengths of the 4 blades in the warp, weft and bias directions were expressed as percentages of the maximum blade width. The coefficient of variation of the stab cut lengths for each permutation was used to determine variability of results. The results from each direction were compared with the stab cut lengths in paper.

3.2 Weapon-force profiles

Dixon's Q test was carried out on the maximum peak forces to identify any outliers. After careful consideration, it was decided that all the results should be retained due to recognition of the natural variability as the weapon contacted the fabric. This became a prominent part of the research.

Samples were prepared to accommodate 5 tests per permutation, which is an adequate number according to British Standards textile testing methods. Unfortunately, from the 170 stab cuts, four results were removed due to the fabric slipping in the clamp which gave falsely high readings. It may be argued that this is an alternative reason for other higher forces in the results, however, those results presented here are done so with confidence. The 4 tests were unable to be replaced due to lack of availability of the test equipment. The remaining number of tests was still deemed sufficient at the testing stage as some textile test methods only require 4 samples (M&S).

The mean values for the maximum force are offered with the graphs together with the coefficient of variation (CV) - a measurement derived from the maximum forces achieved for each set of samples. These will be discussed in section 3.3. An acceptable figure for reliable results for is <3%.

Every stab was recorded in graphical format at 2 speeds: 100mm/min and 2000mm/min (figures 13&14). Each weapon-force profile displays 4 distinct sections, 3 of which display a visual representation of the 3 actions (in bold) that occur as a weapon penetrates fabric [92]; descriptions accompany each graph. The area prior to A is incidental as it represents the descension of the knife towards the fabric:

- Section A – From push to peak. This area shows how far the weapon must **push** onto or into the fabric to reach peak force.
- Section B – From peak to plateau. This area displays the continuing forces necessary to penetrate as the weapon **cuts** or **tears** through the fabric.
- Section C – Force plateau. This area is where the force has reached a plateau as it continues through the fabric.

The extension (mm) is a measurement of how far the weapon has descended from its starting point. The penetration depths discussed in the results are reported with the pre section A extension (descension) removed.

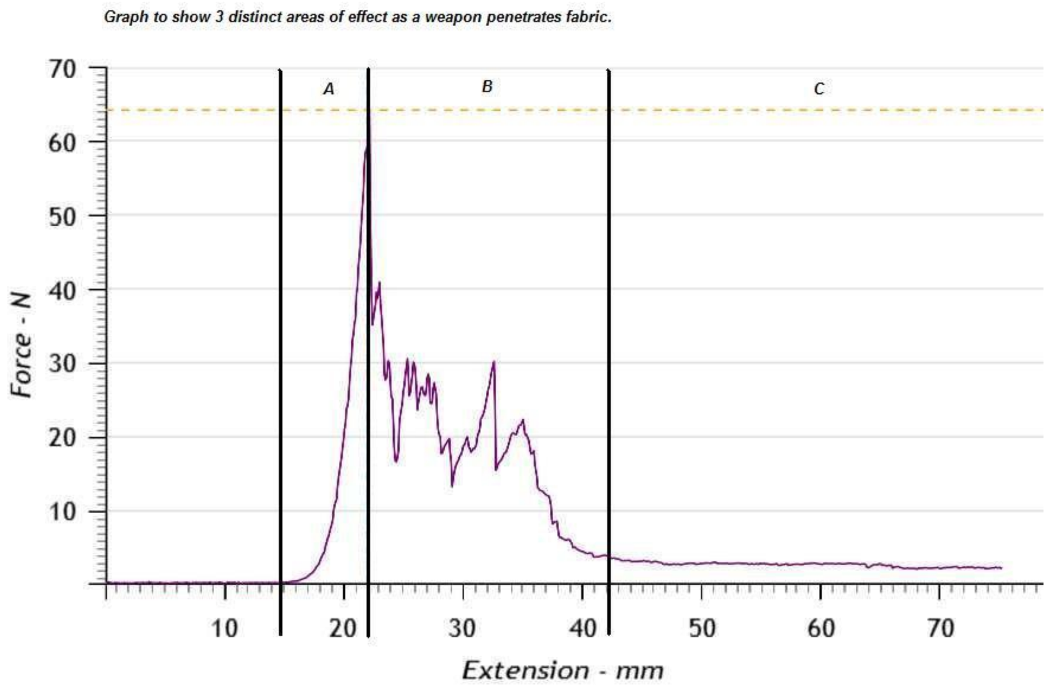


Figure 13: A weapon-force profile created at 100mm/min indicating the 3 sections.

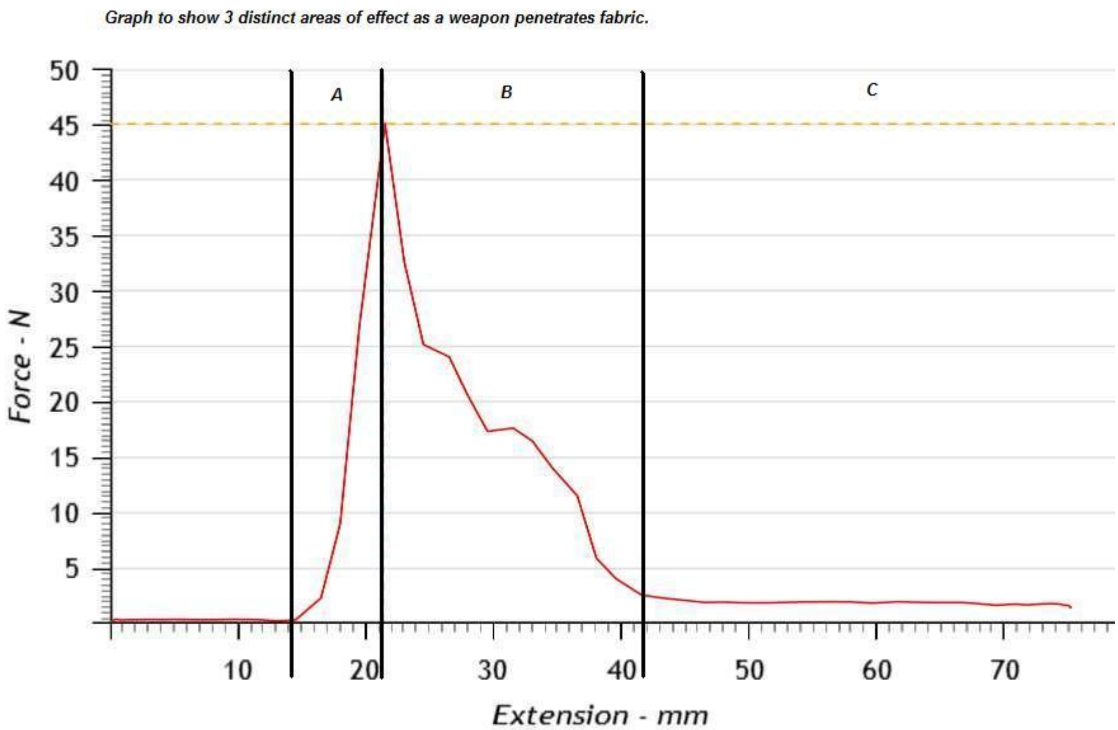


Figure 14: A weapon-force profile created at 2000mm/min indicating the 3 sections.

Representative graphs from each permutation are presented here. As expected, more detail was recorded at the slower speed (figure 13), particularly in section B. The faster tests were not without value as the gross morphology was recorded (figure 14).

3.2.1 Breadknife

The profiles for the breadknife stabbed into fabric were each recorded separately and so representative graphs are shown. The full test reports can be seen in appendices 1 to 7.

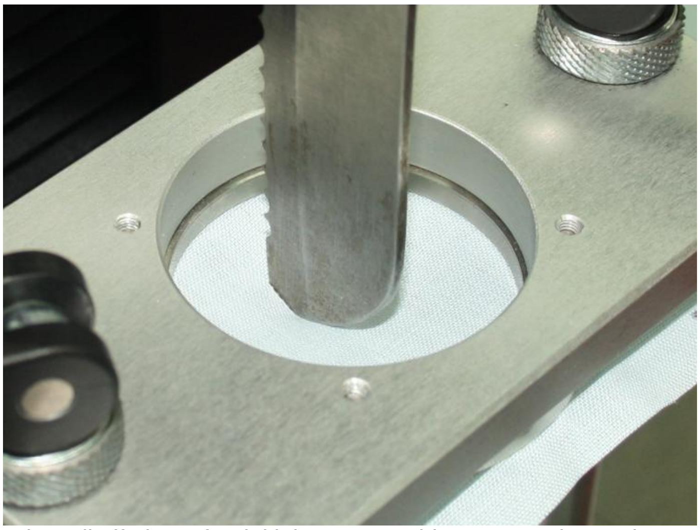


Figure 15: The breadknife just after initial puncture; this was not always the maximum force.

When the weapon-force profiles created at 100mm/min in the warp (figure 16), weft (figure 17) and bias directions (figure 18) are compared before measurements are made, they have variable initial peaks but similar jagged appearances overall.

For section A, the maximum force in each direction occurred at penetration depths of an average of 6mm. This was not the first peak in every test (figure 15) – the maximum force appeared at either the first, second, third or fourth peak (see appendices 1, 3 and 5).

Section B on every graph consists of a long curve of many small peaks. This spans penetration depths from 6mm to 27.5mm in the warp and from 6mm to 28mm in the weft and the bias. The small peaks do not exactly correspond with the number of teeth on the blade. Approximately half way along this curve the mini peaks continue but either briefly increases in height or plateau as the knife blade widens.

The section C plateau begins at an average penetration depth of 27.5mm in the warp, with small fluctuating forces up to 4N. In the weft the plateau begins at an average of 28mm depth with fluctuating forces under 1.5N. In the bias the plateau also begins at 28mm but registers small fluctuating forces up to 5N.

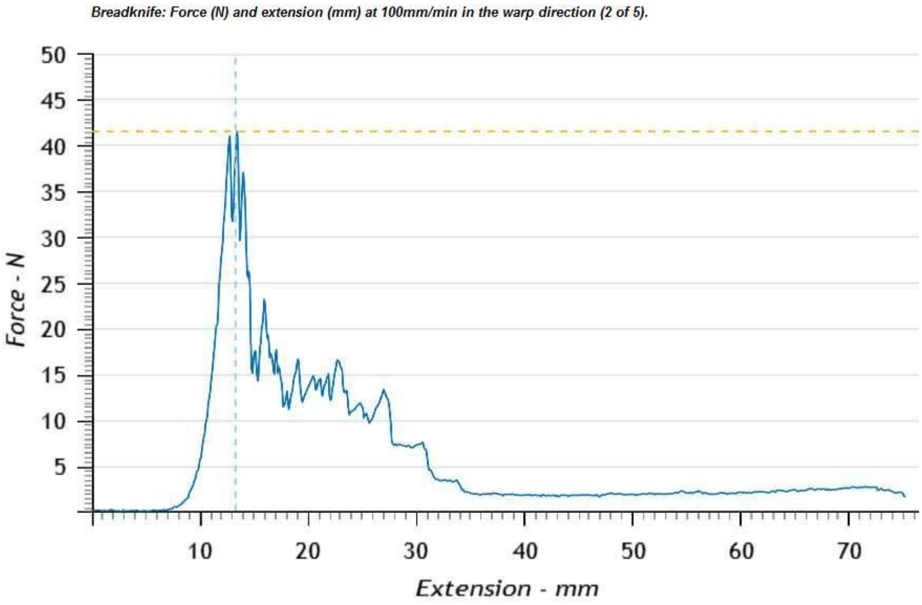


Figure 16: Weapon-force profile (n=1) for the breadknife at 100mm/min in the warp direction. Mean maximum force of 5 samples is 41.07N, coefficient of variation is 2.72%.

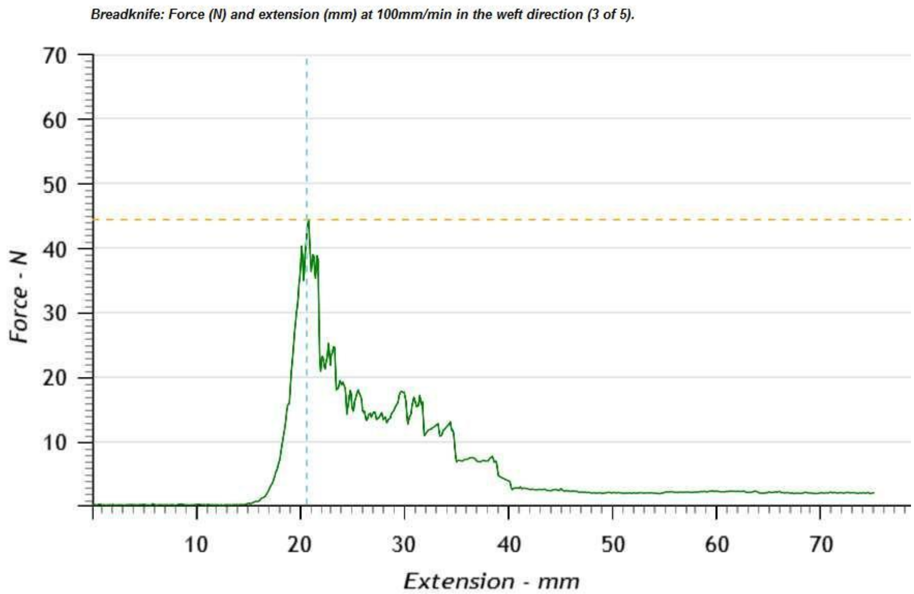


Figure 17: Weapon-force profile (n=1) for the breadknife at 100mm/min in the weft direction. Mean maximum force of 4 samples is 49.57N, coefficient of variation is 9.67%.

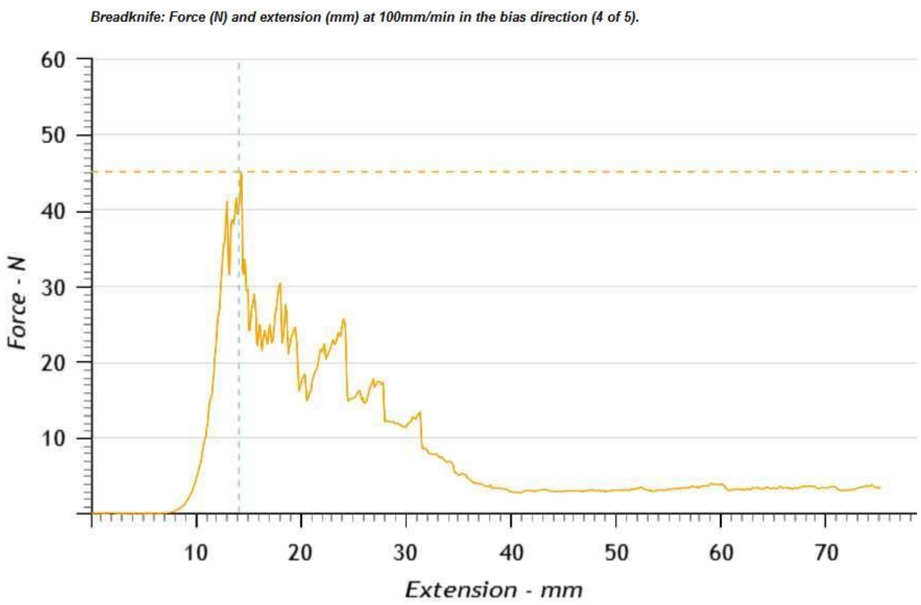


Figure 18: Weapon-force profile (n=1) for the breadknife at 100mm/min in the bias direction. Mean maximum force of 5 samples is 45.42N, coefficient of variation is 10.94%.

When the weapon-force profiles created at 2000mm/min in the warp (figure 19), weft (figure 20) and bias directions (figure 21) are compared before measurements are made, differences are observable regarding the shape at the maximum initial peaks and the variable body of the graphs.

For section A, the maximum force in each direction occurred at penetration depths of an average of 6.5mm in the warp, and 7.5mm in the weft and bias directions. One sample in the bias produced a plateaued peak.

Section B on every graph consists of a curve with gentle undulations. These span average penetration depths from 6.5mm to 31mm in the warp, 7.5mm to 30.5mm in the weft, and from 7.5mm to 30mm in the bias. The widening of the knife is seen visually in most graphs as either a plateauing of the curve, or in a peak (see appendices 2, 4 and 6).

The section C plateau begins at an average penetration depth of 31mm in the warp, with forces up to 4N with little fluctuation. In the weft the plateau begins at an average of 30.5mm with forces under 3.5N with little fluctuation. In the bias the plateau begins at 30mm at around 4N. At approximately half way this rises to 6N, reflecting the widening of the blade.

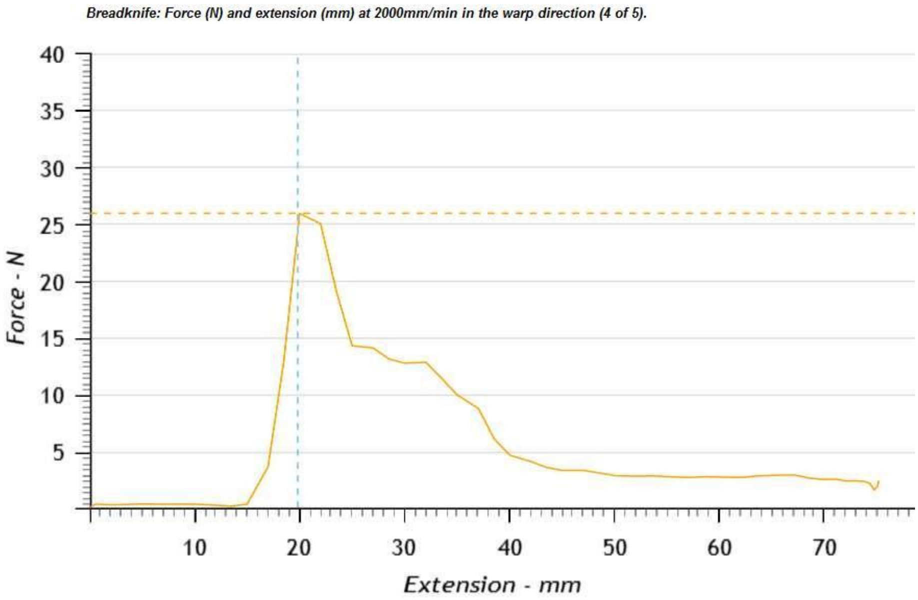


Figure 19: Weapon-force profile (n=1) for the breadknife at 2000mm/min in the warp direction. Mean maximum force for 5 samples is 28.37N, coefficient of variation is 11.76%.

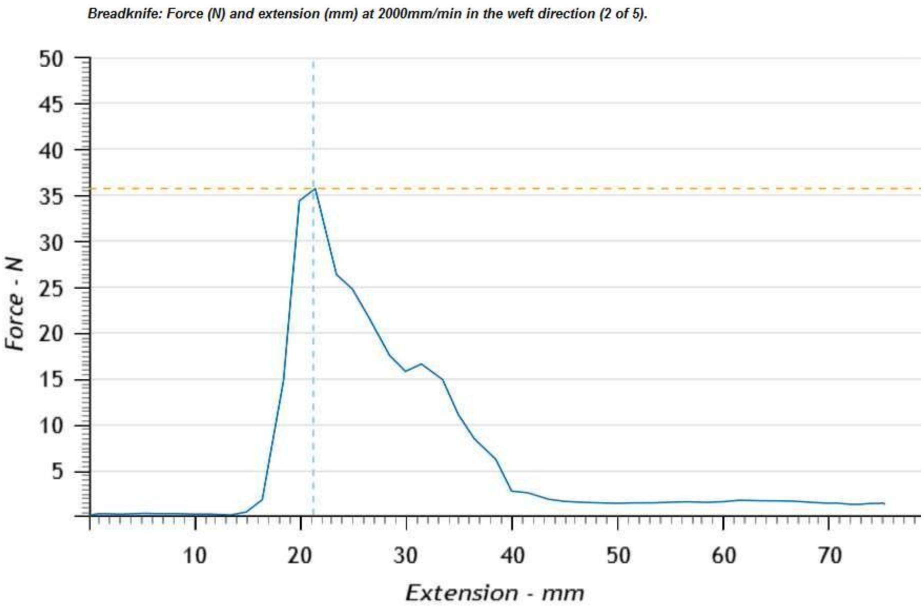


Figure 20: Weapon-force profile (n=1) for the breadknife at 2000mm/min in the weft direction. Mean maximum force for 4 samples is 35.45N, coefficient of variation is 6.21%.

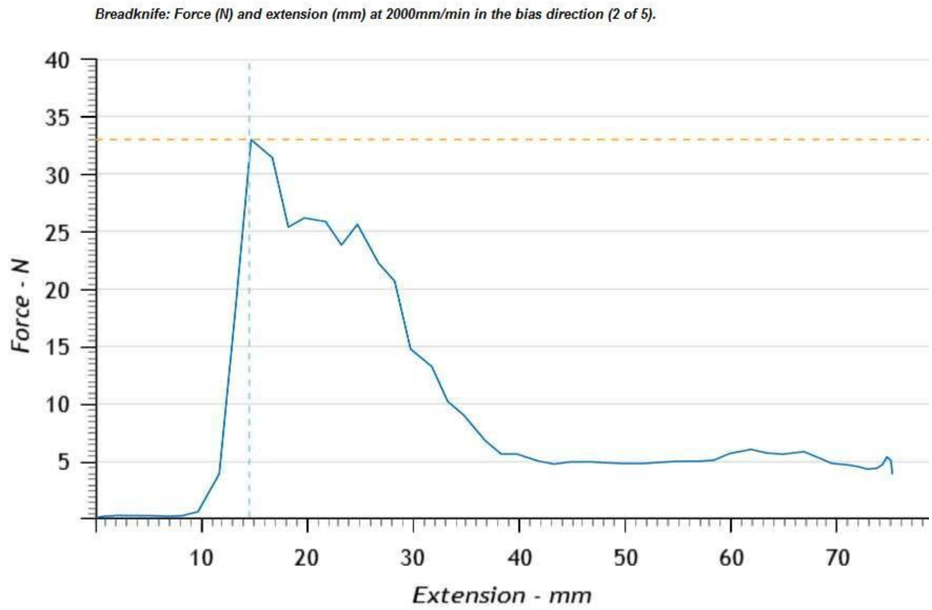


Figure 21: Weapon-force profile (n=1) for the breadknife at 2000mm/min in the bias direction. Mean maximum force for 5 samples is 33.37N, coefficient of variation is 3.78%.

Weapon-force profiles were created into paper (figure 22) at 100mm/min as a non-woven medium for comparison with a woven fabric. The CV was expected to be low, but at 8.95% it did not meet expectations. The blade punctures at around 7mm and then the downward slope that follows is irregular but captures the damage behind the tip of the blade. The remainder of the combined profile consists of 23 peaks – this matches the number of teeth on the blade that penetrated the paper. The heights of the peaks vary as the force changes. The bases of the last 11 peaks are slightly higher in force as this reflects the slight widening of the blade. Visually, this breadknife into paper test produced a graph which captures how a blade profile can affect a medium as it penetrates. The detail captured behavioural differences to fabric.

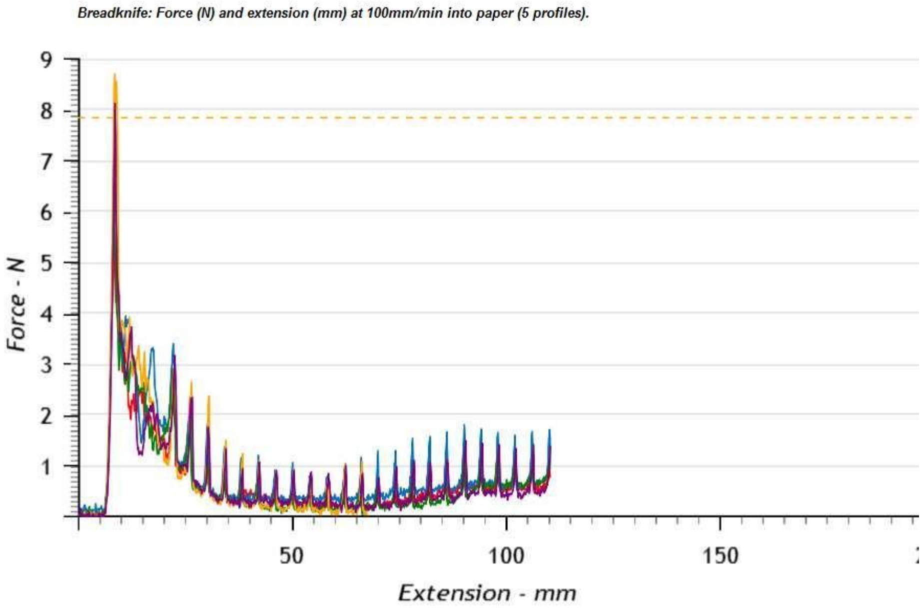


Figure 22: Weapon-force profiles (n=5) for the breadknife at 100mm/min into paper. Mean maximum force is 7.83N, coefficient of variation is 8.95%.

A box plot graph was created to compare the distribution of maximum peak forces (figure 23). When comparing directional force at 100mm/min, the warp and weft remain separate – the warp always requires less force to puncture than in the weft with the breadknife at this slower speed. The bias data overlaps both directions. At 2000mm/min, the forces recorded are possible in any direction. There is no overlap of data between speeds.

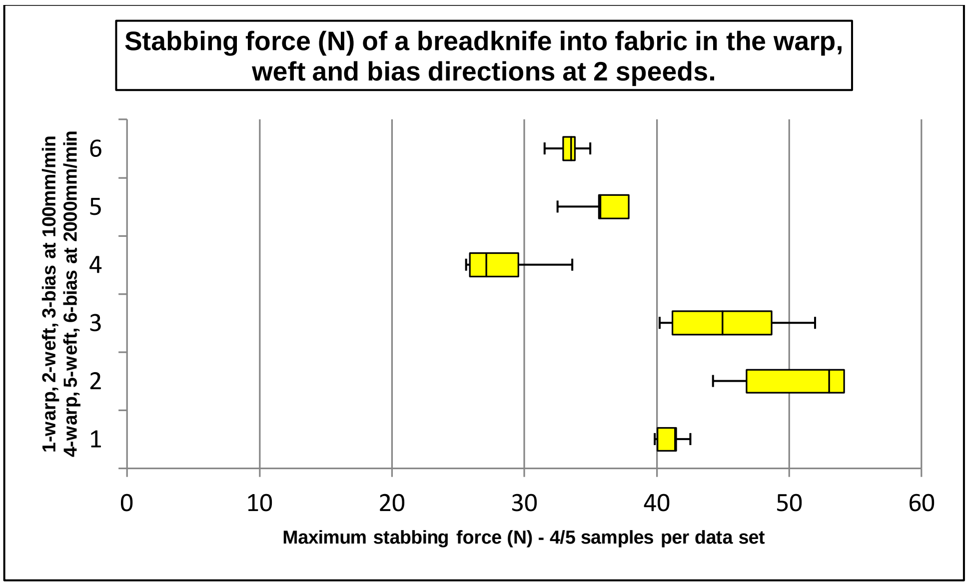


Figure 23: Maximum forces achieved by the breadknife in the warp, weft and bias at 2 speeds into fabric.

3.2.3 Single edged blade with a straight spine

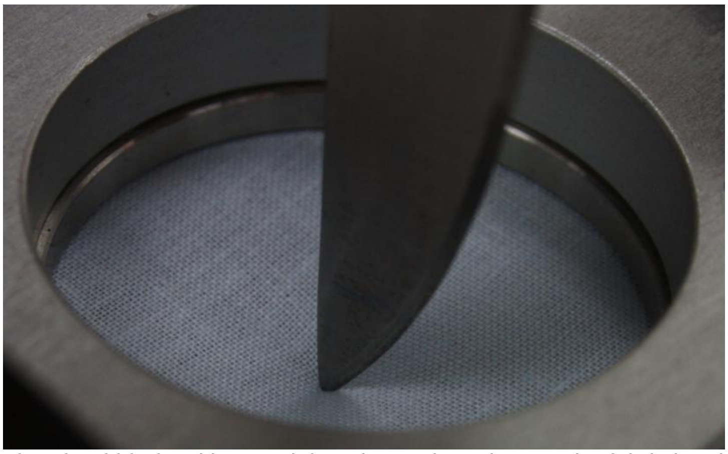


Figure 24: The single edged blade with a straight spine as it pushes on the fabric just before penetration.

When the combined weapon-force profiles created at 100mm/min in the warp (figure 25), weft (figure 26) and bias directions (figure 27) are compared before measurements are made, they have a similar overall appearance. The full test reports can be seen in appendices 8-14.

For section A, the knife pushed onto the fabric (figure 24) to a depth of 5mm before achieving the maximum force, in every direction. The nature of the graphs renders it difficult to separate the data more accurately.

In section B on all 3 graphs, after the initial peak there is a trough to a minimum of 1N; the line fluctuates. There is a second and final peak at a penetration depth of 20mm. This peaks to a maximum of 6N in the warp, 4N in the weft and 4.5N in the bias direction. This is where the knife blade widens after the tip and it continues to force through the fabric.

For each direction, the section C plateau begins around 30mm penetration depth at a force which fluctuates but remains less than 1N. At half way along the plateau, the fluctuating plateau continues but rises slightly to 1.5N. This reflects the gradual widening along the blade.

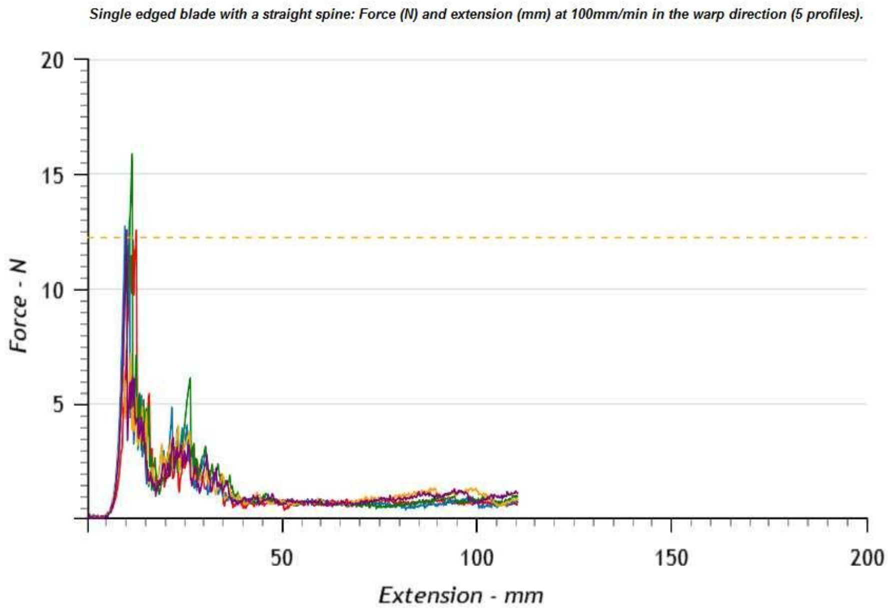


Figure 25: Weapon-force profiles (n=5) for the single edged blade with a straight spine at 100mm/min in the warp direction. Mean maximum force is 12.21N, coefficient of variation is 25.82%.

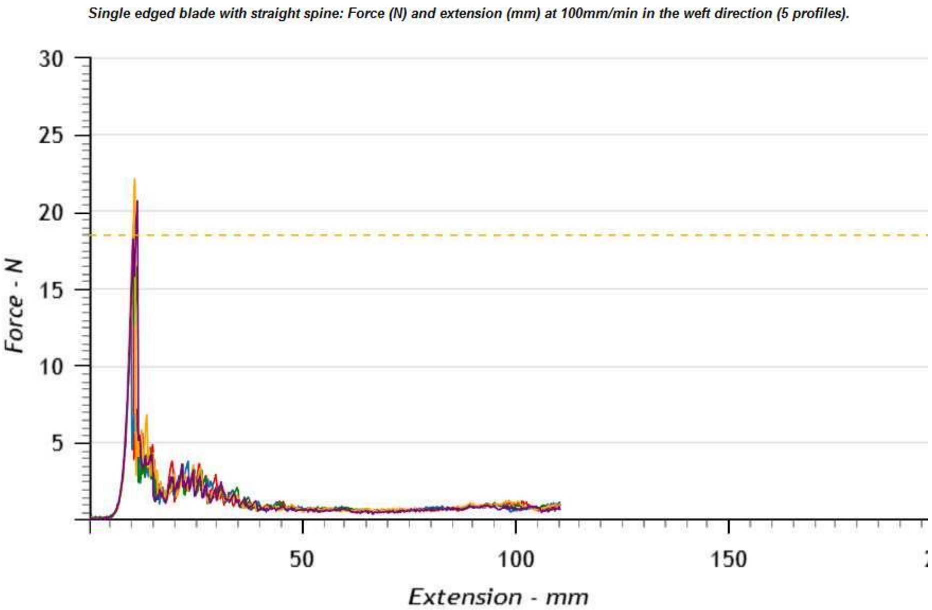


Figure 26: Weapon-force profiles (n=5) for the single edged blade with a straight spine at 100mm/min in the weft direction. Mean maximum force is 18.43N, coefficient of variation is 18.67%.

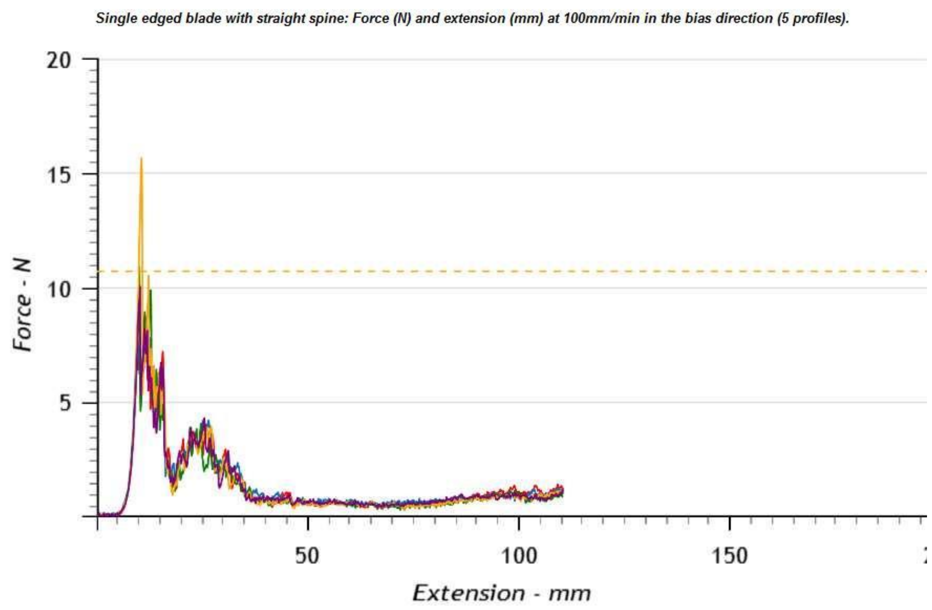


Figure 27: Weapon-force profiles (n=5) for the single edged blade with a straight spine at 100mm/min in the bias direction. Mean maximum force is 10.67N, coefficient of variation is 27.85%.

When the combined weapon-force profiles created at 2000mm/min in the warp (figure 28), weft (figure 29) and bias directions (figure 30) are compared, the first peak appears most uniform in the bias.

For section A, the penetration depths to achieve the maximum force in the warp and weft and bias are all around 5mm.

In section B on all 3 graphs, after the initial peak there is a trough to a minimum of 1.75N in the warp, 1.4N in the weft and 2N in the bias direction. There is a second and final peak at a penetration depth of 20mm in each direction and the forces are a maximum of 4.25N in the warp, 3.2N in the weft and 3.75N in the bias direction. This is where the knife blade widens after the tip and it continues to force through the fabric.

The section C plateau in all directions begins around 30mm penetration depth at a force which fluctuates but remains around, and less than 1N. At half way along the fluctuating plateau, it continues but rises slightly to 1.5N. This reflects the gradual widening along the blade. The graph for the weft direction at 2000mm/min (figure 27) is scaled up to clarify the measurements as the plateau has achieved readings as low as 0.3N.

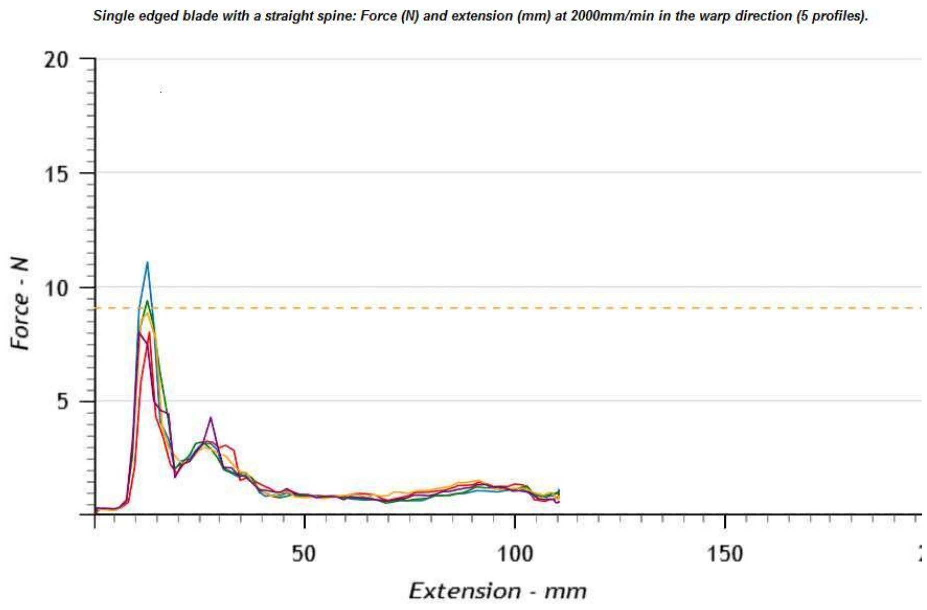


Figure 28: Weapon-force profiles (n=5) for the single edged blade with a straight spine at 2000mm/min in the warp direction. Mean maximum force is 9.02N, coefficient of variation is 14.08%.

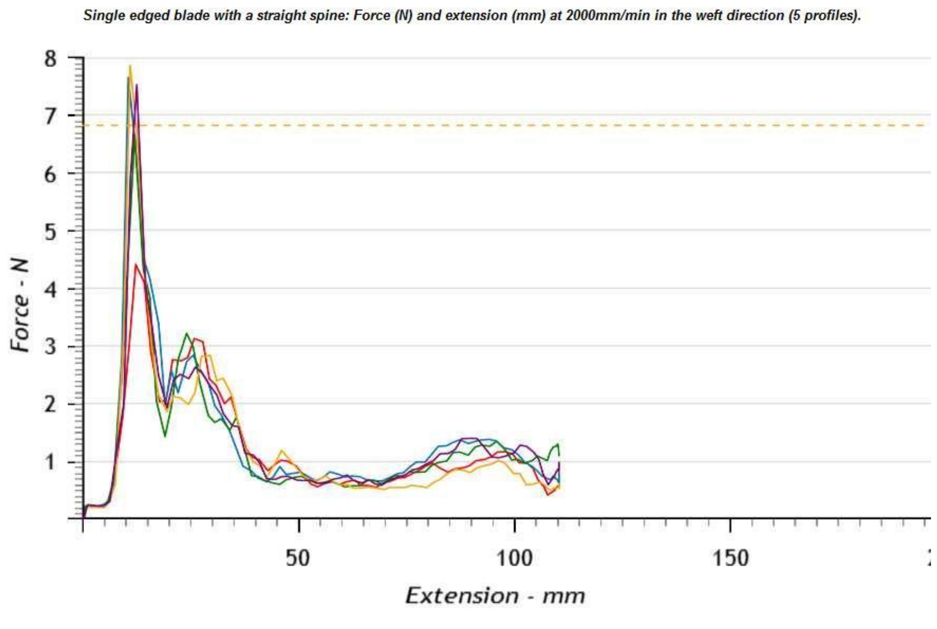


Figure 29: Weapon-force profiles (n=5) for the single edged blade with a straight spine at 2000mm/min in the weft direction. Mean maximum force is 6.80N, coefficient of variation is 20.93%.

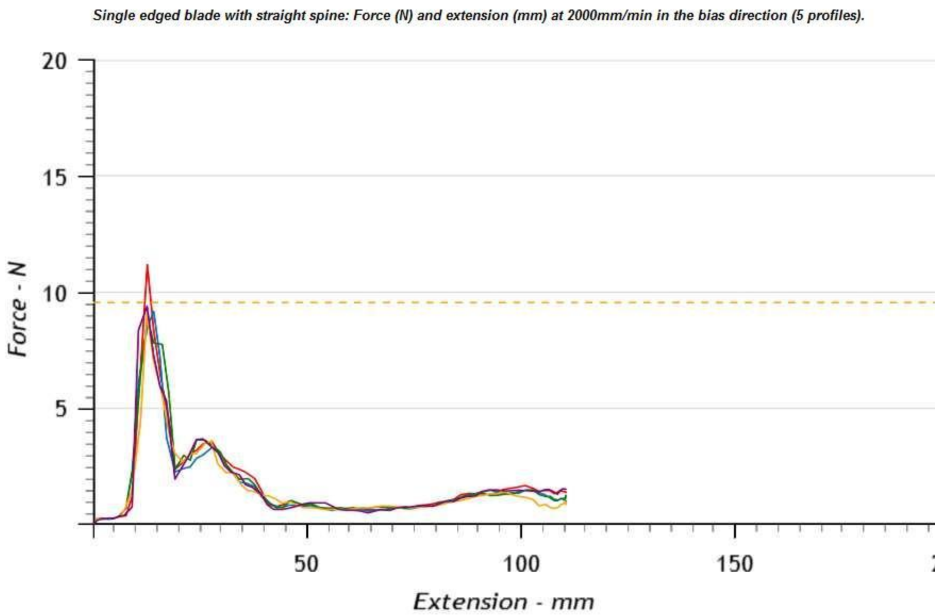


Figure 30: Weapon-force profiles (n=5) for the single edged blade with a straight spine at 2000mm/min in the bias direction. Mean maximum force is 9.50N, coefficient of variation is 9.78%.

Weapon-force profiles were created into paper (figure 31) at 100mm/min as a non-woven medium for comparison with a woven fabric. The CV was expected to be low - at 14.81% it did not meet expectations. It differs to the profiles in fabric as after the initial trough, the knife cuts smoothly through with no further second peak.

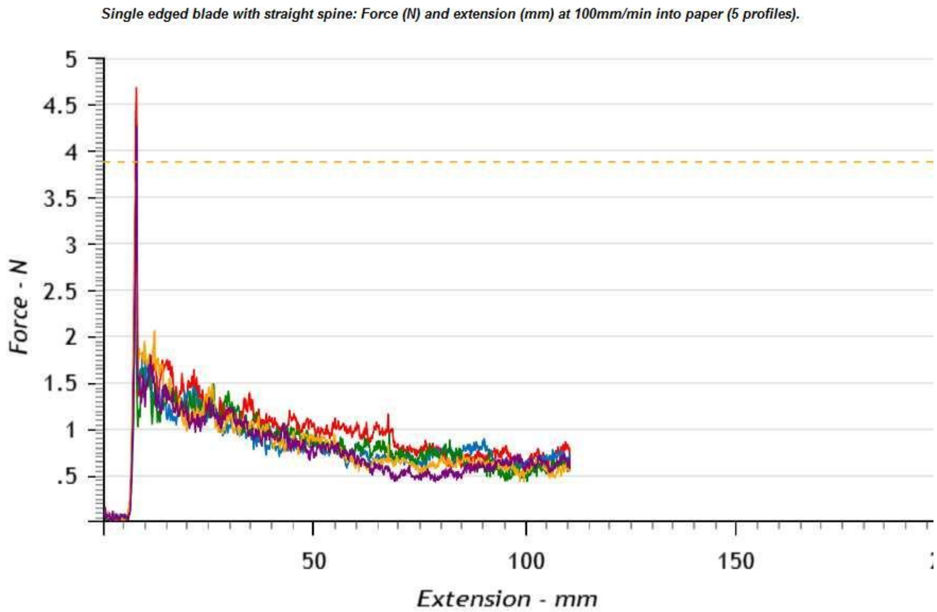


Figure 31: Weapon-force profiles (n=5) for the single edged blade with a straight spine at 100mm/min into paper. Mean maximum force is 3.87N, coefficient of variation is 14.81%.

A box plot graph was created to compare the distribution of maximum peak forces (figure 32). At 100mm/min there is an overlap of data in every direction. At 2000mm/min, the weft marginally achieves the lowest forces in every case, and the warp and bias overlap. There is an expectation that the faster speeds will require less force, however, the lowest maximum force achieved in the warp and bias at 100mm/min were less than some of those achieved in the warp and bias at 2000mm/min.

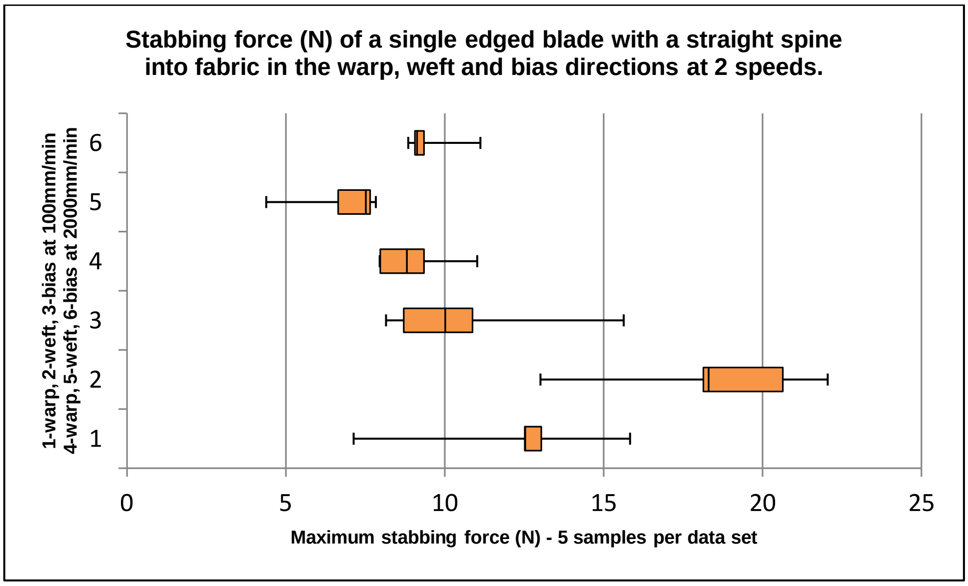


Figure 32: Maximum forces achieved for the single edged blade with a straight spine in the warp, weft and bias directions at 2 speeds into fabric.

3.2.3 Single edged blade with a curved spine

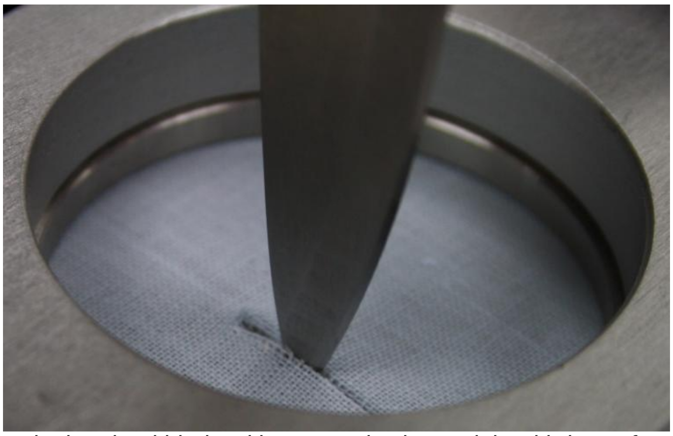


Figure 33: The single edged blade with a curved spine as it is withdrawn from the stab cut.

When the combined weapon-force profiles created at 100mm/min in the warp (figure 34), weft (figure 35) and bias directions (figure 36) are compared before measurements are made, they have a similar overall appearance. The CV is the largest found in this study at 40.55%. The full reports can be seen in appendices 15-21.

For section A, the penetration depths to achieve the maximum force in each direction are all around 5mm. The nature of the graphs and close data renders it difficult to separate the data more accurately.

In section B in all 3 directions there is no distinct pattern after the initial puncture. In the weft and bias at least one other significant peak can be seen next which in some cases is as larger than the maximum force for another sample in the same direction. Part of the tip is damaged and slightly flattened - the multiple high peaks could be a record of the tip severing individuals yarn by tearing, as oppose to easily cutting through. Next, each graph displays a wave consisting of mini peaks through a range of 1.5-6N in the warp, 1.5-5.5N in the weft and 2-6N in the bias. A long and curved final peak occurs at penetration depths from 12.5mm to 67.5mm in the warp, 12.5mm to 70mm in the weft, and from 15mm to 70mm in the bias. This is where the knife blade continues to widen reaching maximum forces of 5N in the warp, weft and bias.

The section C plateau begins at a penetration depth of 67.5mm in the warp, with small fluctuating forces between 0.5N and 2 N. In the weft the plateau begins at 70mm depth with slightly larger fluctuating forces at 1N and 2.75N. In the bias the plateau begins at 70mm and registers small fluctuating forces between 1.5N and 3N. This reflects the minimal widening along the remainder of the blade.

As the knife was stationary and the point was central to the cut (figure 33), during testing the knife spine was observed pushing against the side of the cut. This could be partly responsible for the sustained forces observed above.

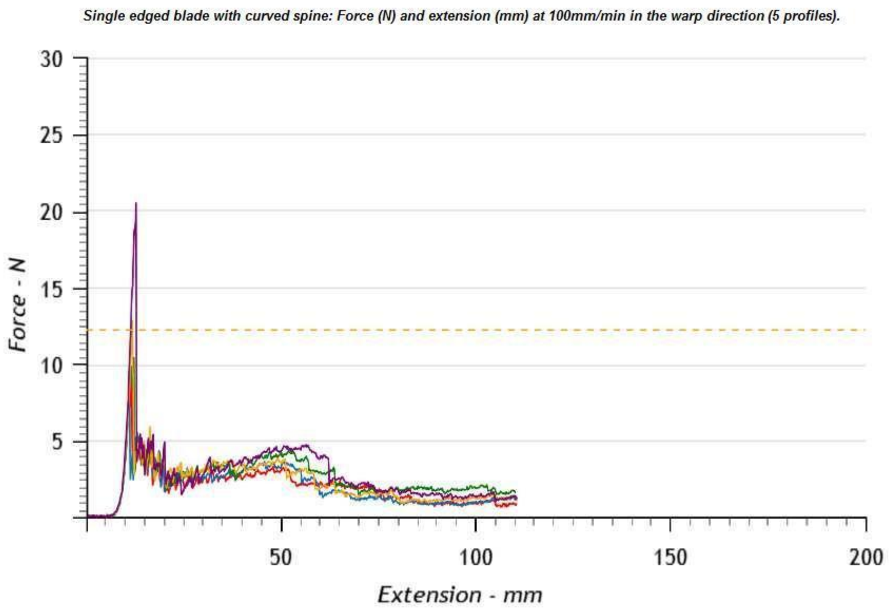


Figure 34: Weapon-force profiles (n=5) for the single edged blade with a curved spine at 100mm/min in the warp direction. Mean maximum force is 12.20N, coefficient of variation is 40.55%.

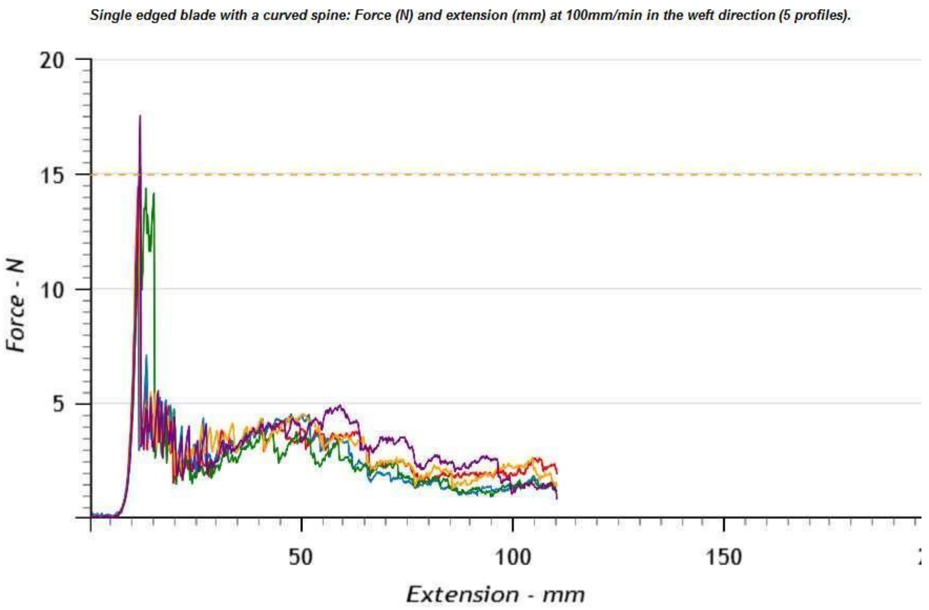


Figure 35: Weapon-force profiles (n=5) for the single edged blade with a curved spine at 100mm/min in the weft direction. Mean maximum force is 14.92N, coefficient of variation is 10.68%.

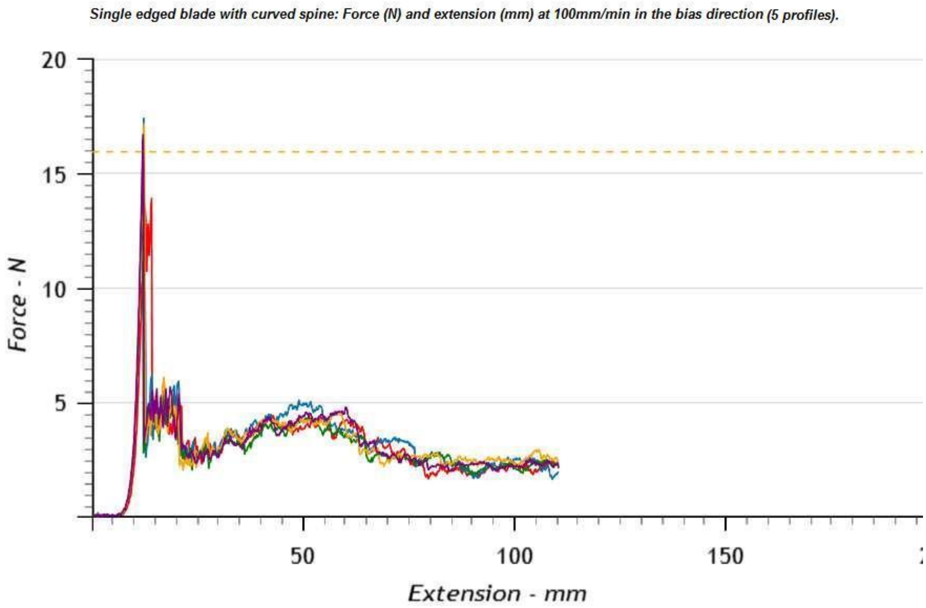


Figure 36: Weapon-force profiles (n=5) for the single edged blade with a curved spine at 100mm/min in the bias direction. Mean maximum force is 15.90N, coefficient of variation is 10.10%.

When the combined weapon-force profiles created at 2000mm/min in the warp (figure 37), weft (figure 38) and bias directions (figure 39) are compared before measurements are made, they have a similar overall appearance.

For section A, the penetration depths to achieve the maximum forces in the warp are between 7.5mm and 10mm. In the weft 5mm-7.5mm, and more variable in the bias at between 5mm and 10mm.

In section B in the warp and weft, 2 samples display a small plateau at the initial puncture. In the weft, a further 2 samples (in green and purple – figure 36) have a stepped peak, where the maximum force occurs just after the initial puncture. This is possibly due to part of the tip being damaged and slightly flattened. This is not displayed in the bias, possible due to the yarns moving apart more readily. The trough which follows the initial penetration dips to as low as 2.3N in the warp, 2.6N in the weft and 2.4N in the bias. Each graph then displays a long and curved final peak occurring at penetration depths from 17.5mm to 67.5mm in the warp, 15mm to 80mm in the weft, and from 17.5mm to 80mm in the bias. This is where the knife blade continues to widen achieved maximum forces of 5.7N in the warp, 5.5N in the weft and 4.7N in the bias.

The section C plateau begins at a penetration depth of 67.5mm in the warp, with small fluctuating forces between 0.6N and 2.4N. In the weft the plateau begins at 80mm depth with fluctuating forces between 0.8N and 2.6N. In the bias the plateau also begins at 80mm depth and registers small fluctuating forces between 1.5N and 3N – as it does at the slower speed. This reflects the minimal widening along the blade.

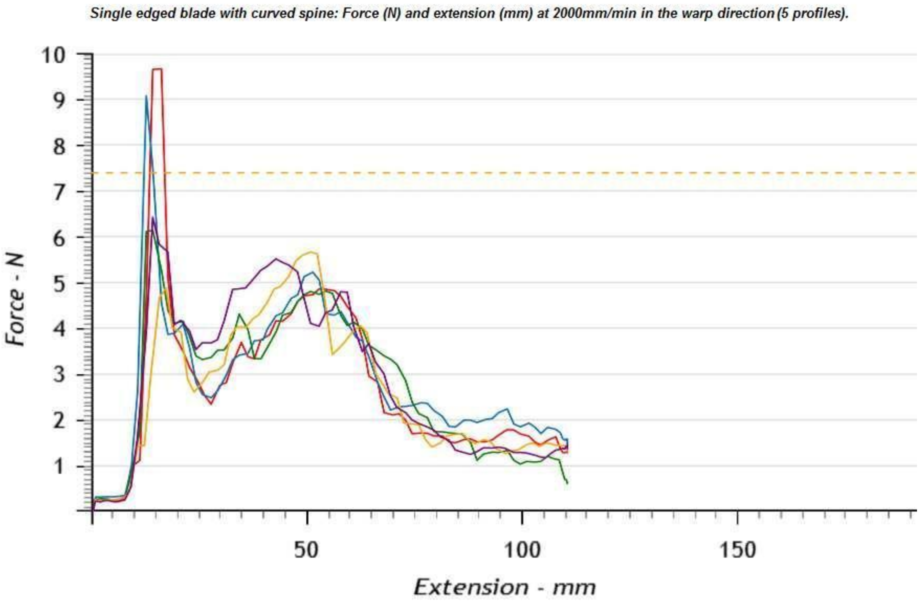


Figure 37: Weapon-force profiles (n=5) for the single edged blade with a curved spine at 2000mm/min in the warp direction. Mean maximum force is 7.38N, coefficient of variation is 24.94%.

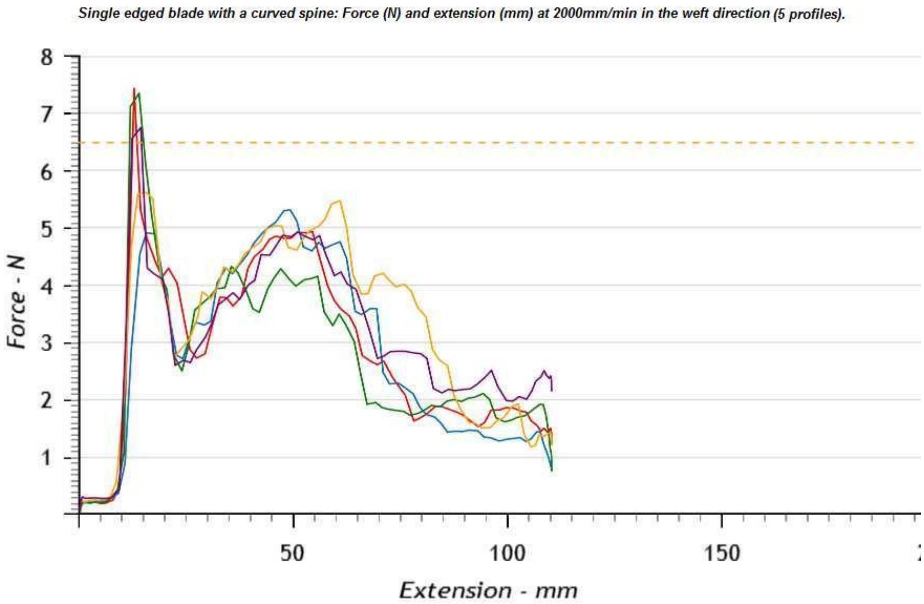


Figure 38: Weapon-force profiles (n=5) for the single edged blade with a curved spine at 2000mm/min in the weft direction. Mean maximum force is 6.48N, coefficient of variation is 15.14%.

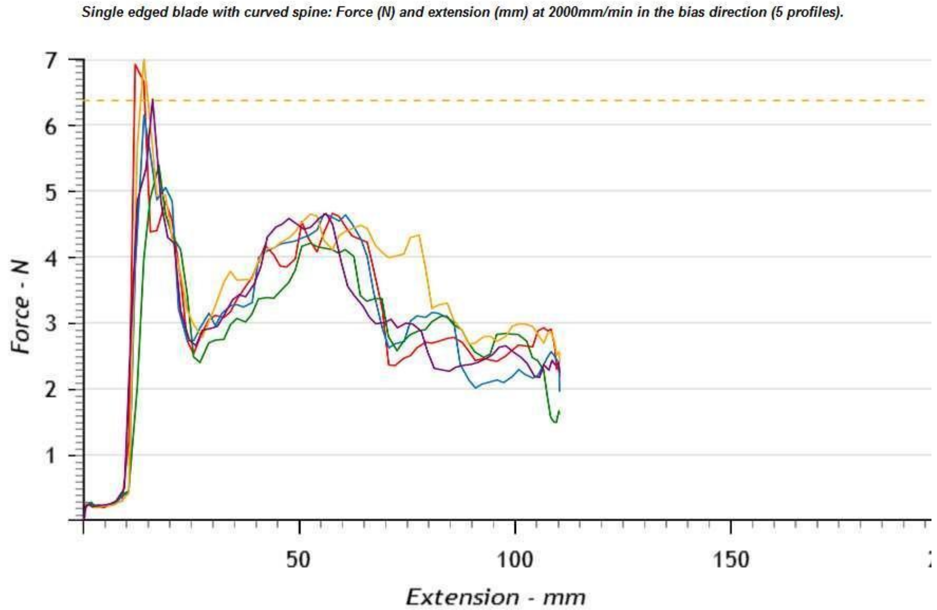


Figure 39: Weapon-force profiles (n=5) for the single edged blade with a curved spine at 2000mm/min in the bias direction. Mean maximum force is 6.36N, coefficient of variation is 10.31%.

Weapon-force profiles were created into paper (figure 40) at 100mm/min as a non-woven medium for comparison with a woven fabric. The CV was expected to be low but at 14.77% was higher than expected. To display the variation of the individual profiles of the stab cuts into paper more clearly, they were spread out after testing, but would normally have been overlaid.

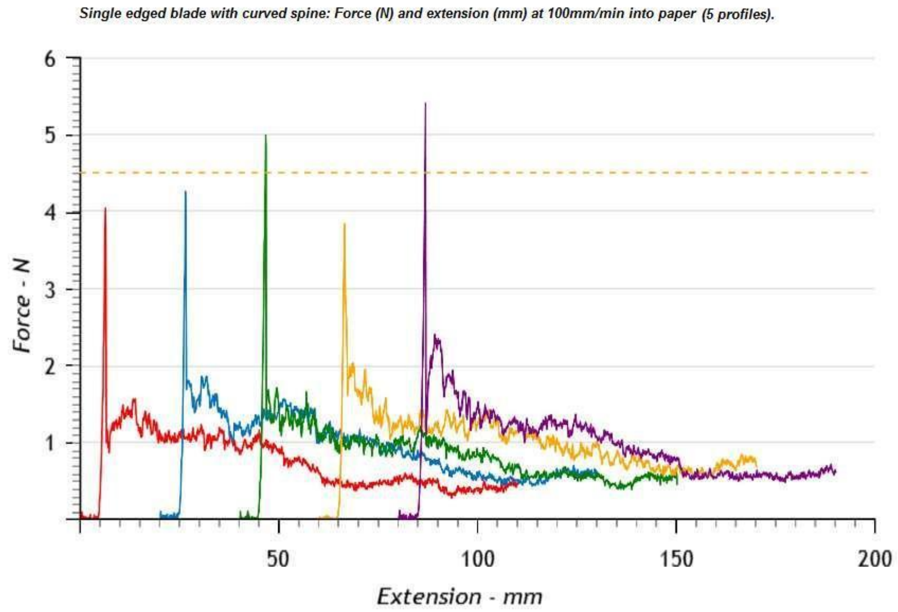


Figure 40: Weapon-force profiles (n=5) for the single edged blade with a curved spine at 100mm/min into paper, with a staggered display. Mean maximum force is 4.50N, coefficient of variation is 14.77%.

A box plot graph was created to compare the distribution of maximum peak forces (figure 41). At 100mm/min there is a overlap of data in every direction. At 2000mm/min, there is also an overlap of data in every direction. There is an expectation that the faster speeds will require less force, however, the lowest maximum force achieved in the warp at 100mm/min was less than some of those achieved in the warp and weft at 2000mm/min.

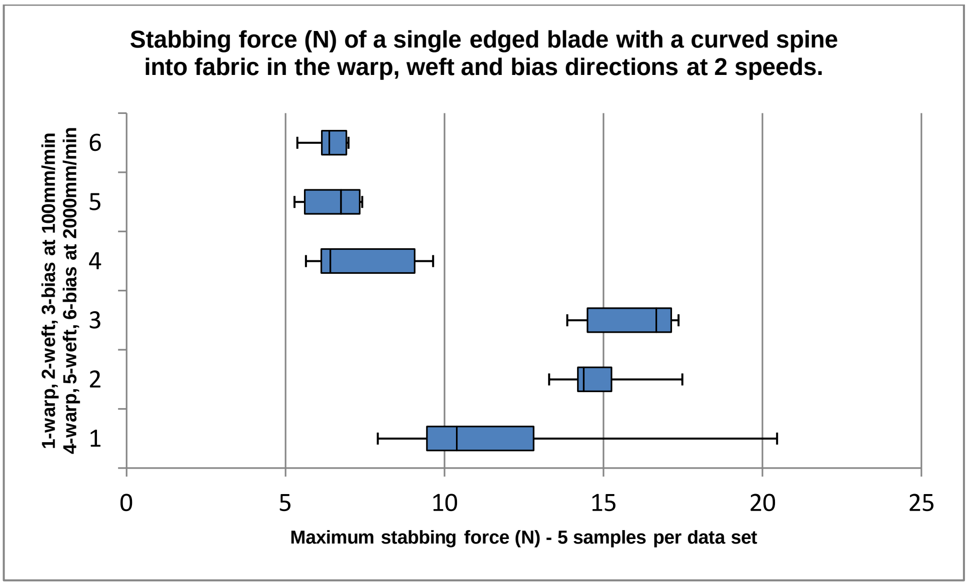


Figure 41: Maximum forces achieved by the single edged blade with a curved spine in the warp, weft and bias directions at 2 speeds into fabric.

3.2.4 Double edged blade

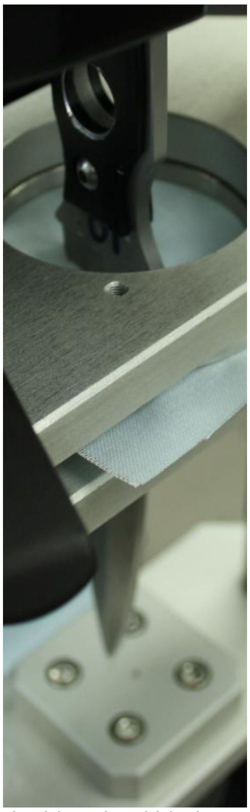


Figure 42: The double edged blade at full penetration.

When the combined weapon-force profiles created at 100mm/min in the warp (figure 43), weft (figure 44) and bias directions (figure 45) are compared before measurements are made, they display similar trends. The full test reports can be seen in appendices 22-28.

For section A, the penetration depths to achieve the maximum force in each direction are all around 7.5mm. The nature of the graphs and close data renders it difficult to separate the data more accurately.

Section B occurs from the peak at 7.5mm penetration for all directions and the plateau at 52.5mm in the warp and bias, and 62.5 in the weft. In the warp and weft, there is a trough followed by a curved peak which then slopes down to the plateau - this is made up of minute peaks and troughs. These could be explained by the blade pushing against the yarns before severing. The bias follows this basic trend, but the one test produced a double peak within the next 5mm.

The section C plateau begins at a penetration depth of 52.5mm in the warp and bias with small fluctuating forces less than 1N. In the weft the plateau of fluctuating forces of less than 1N plateau begins later at 62.5mm. The small force recorded during the plateau reflects the double edged blade as it gradually widens, yet continues to cut with ease until the test terminates at 105mm along the blade (figure 42).

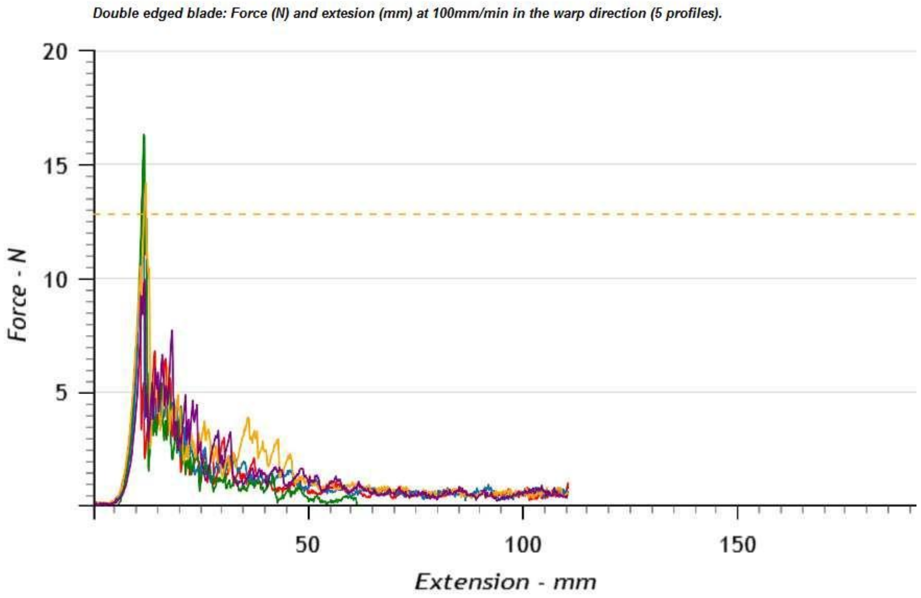


Figure 43: Weapon-force profiles (n=5) for the double edged blade at 100mm/min in the warp direction. Mean maximum force is 12.78N, coefficient of variation is 23.75%.

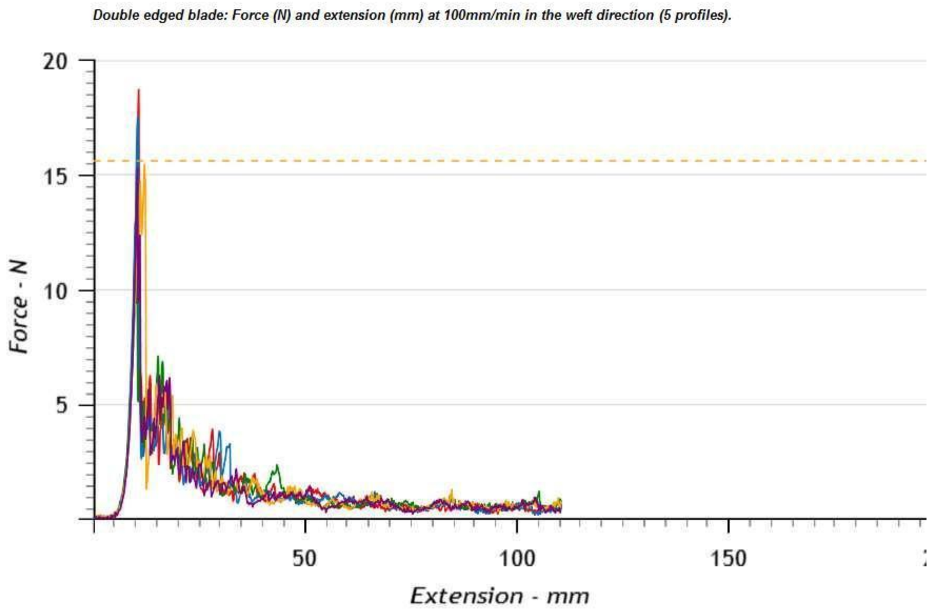


Figure 44: Weapon-force profiles (n=5) for the double edged blade at 100mm/min in the weft direction. Mean maximum force is 15.58N, coefficient of variation is 18.61%.

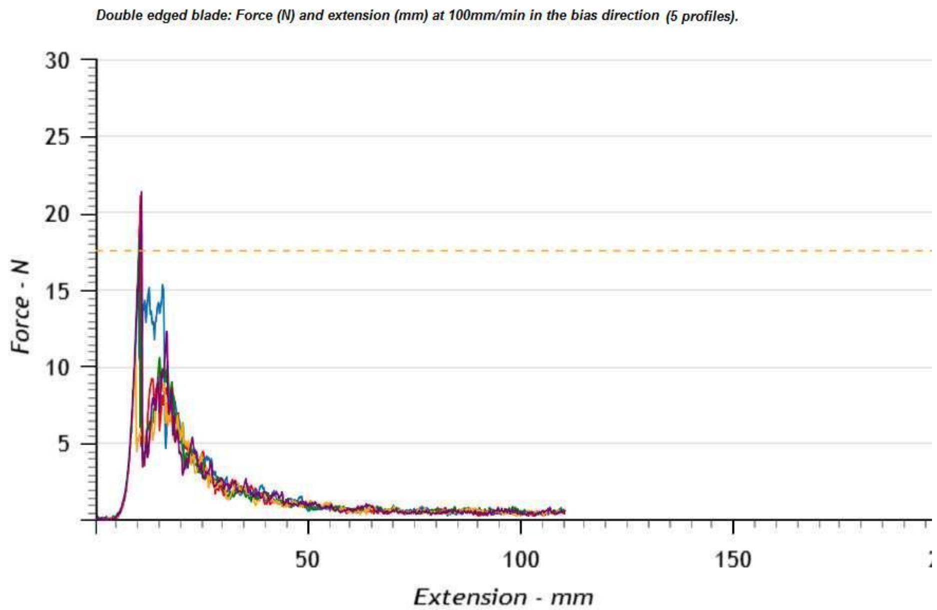


Figure 45: Weapon-force profiles (n=5) for the double edged blade at 100mm/min in the bias direction. Mean maximum force is 17.50N, coefficient of variation is 24.15%.

When the combined weapon-force profiles created at 2000mm/min in the warp (figure 46), weft (figure 47) and bias directions (figure 48) are compared before measurements are made, the warp and weft are visually similar.

For section A, the penetration depths to achieve the maximum force in the warp are all around 10mm. In the weft the depth for the maximum forces ranges from 5mm to 7.5mm. The bias is much more variable - the first maximum force occurs in the first peak at 7.5mm. For the remaining 4 tests, it was the second peak that gave the maximum reading, all at 12.5mm penetration depth.

Section B is from the maximum force penetration in section A until the plateau at section C. All 3 directions display similar characteristics as each other, but there is no sign of the curved peak section seen at the slower speed. The slope which is seen throughout this section consists of peaks and troughs, which could be explained by the blade pushing against the yarns before severing.

The section C plateau begins at a penetration depth of 62.5mm in the warp, 60mm in the weft and 50mm in the bias direction with gently fluctuating forces of less than 1N. The small forces recorded during the plateau reflects the double edged blade as it gradually widens, yet continues to cut with ease until it terminates at 105mm along the blade.

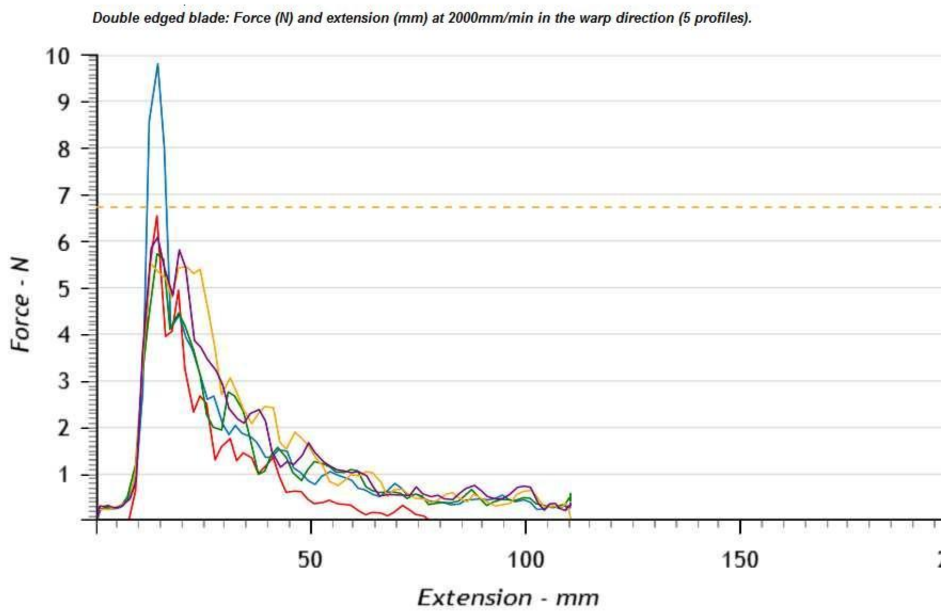


Figure 46: Weapon-force profiles (n=5) for the double edged blade at 2000mm/min in the warp direction. Mean maximum force is 6.72N, coefficient of variation is 26.22%.

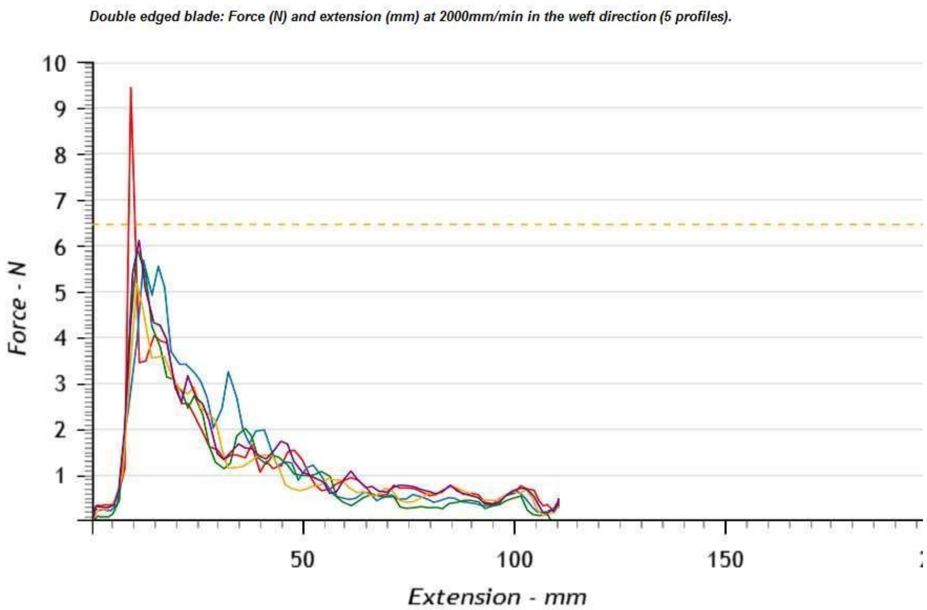


Figure 47: Weapon-force profiles (n=5) for the double edged blade at 2000mm/min in the weft direction. Mean maximum force is 6.45N, coefficient of variation is 26.41%.

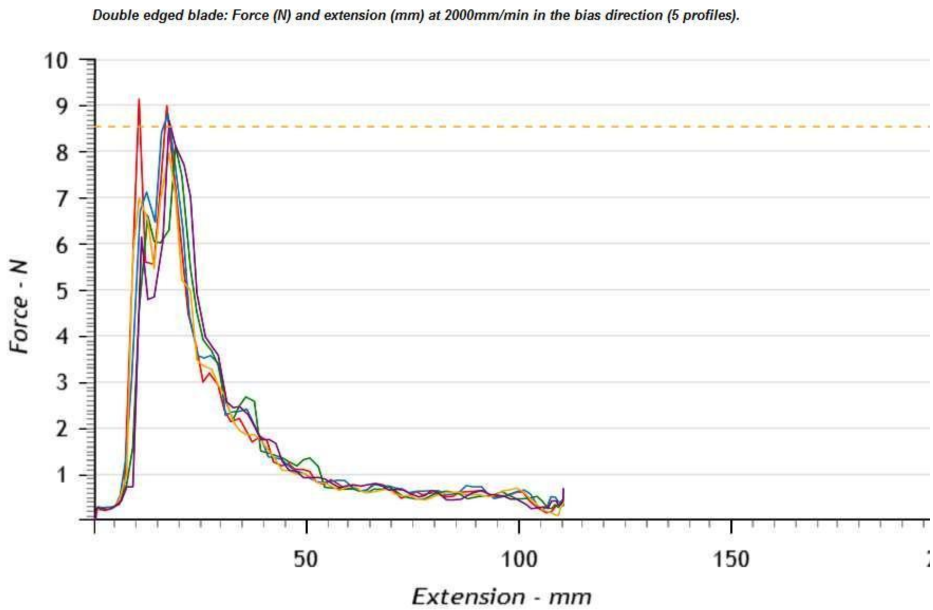


Figure 48: Weapon-force profiles (n=5) for the double edged blade at 2000mm/min in the bias direction. Mean maximum force is 8.52N, coefficient of variation is 5.74%.

Weapon-force profiles were created into paper (figure 49) at 100mm/min as a non-woven medium for comparison with a woven fabric. The CV was expected to be low, but at 5.00% was higher than expected. One profile is shown for illustration; the other 4 can be seen in appendix 28. The warp and bias profiles at the same speed have very similar profiles but at a greater force.

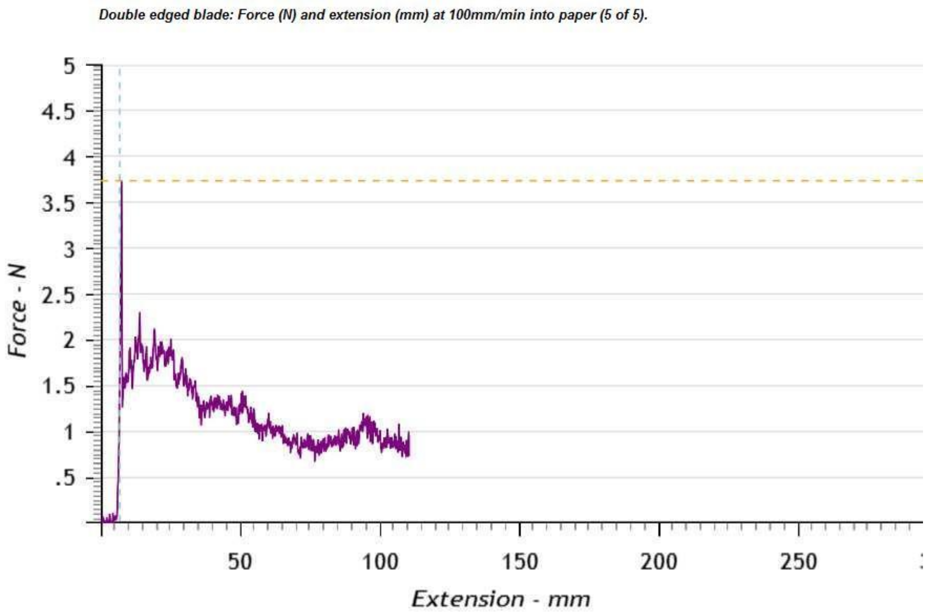


Figure 49: Weapon-force profile (n=1) for the double edged blade at 100mm/min into paper. Mean maximum force for 5 samples is 3.85N, coefficient of variation is 5.00%.

A box plot graph was created to compare the distribution of maximum peak forces (figure 50). At both 100mm/min and at 2000mm/min, there is an overlap of data in every direction, within speeds. There is an expectation that the faster speeds will require less force, however, the lowest maximum force achieved in the warp at 100mm/min was less than some of those achieved in the warp and weft at 2000mm/min.

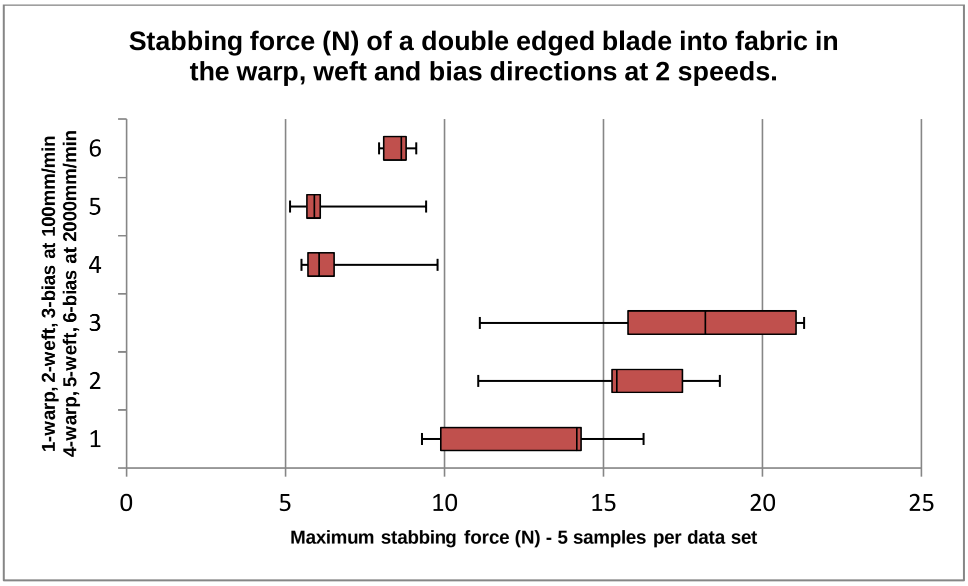


Figure 50: Maximum forces achieved by the double edged blade in the warp, weft and bias directions at 2 speeds into fabric.

3.2.5 Slotted head screwdriver drill bit

Each time the machinery returned to the starting position after testing this weapon, the drill bit which was held in the mount by a strong magnet, remained caught in the fabric (figure 51). This did not occur for the crosshead screwdriver drill bit mounted in the same way. The fabric hole made by the slotted end was smaller than this section of the weapon, and so when the shank was forced in, the weave remained tight and held it in place. The resulting puncture marks in the warp and weft were rectangular with varying degrees of definition; the bias samples either reflected the hexagonal shank or were indistinct. The full test reports can be seen in appendices 29-35.

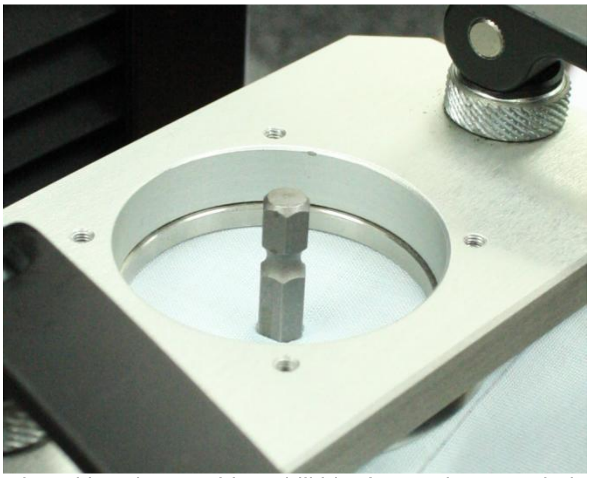


Figure 51: Slotted head screwdriver drill bit after testing, caught in the fabric.

When the combined weapon-force profiles created at 100mm/min in the warp (figure 52), weft (figure 53) and bias directions (figure 54) are compared, the bias appears more uniform than either the warp or weft. The graphs lines do not consist of mini peaks as the bladed weapons do.

For section A, the range of penetration depths to achieve the maximum peak force for the fabric to puncture vary as follows: warp - 6-7.5mm, weft – 6-7mm and bias – 7-7.5mm.

For section B, if this was a regular screwdriver, no further forces would peak as the shank would be narrower than the blade. As this was a screwdriver drill bit, there is a further registering of force due to its shape, although only 2 of the directions have registered the force as the screwdriver blade section of the weapon penetrated the fabric; the maximum force achieved was 19N in the warp and 10N in the weft. In the bias there is no corresponding peak; this may be possibly due to the stretch being greater in the bias direction. The final peak is where the weapon width widens further at 12.5mm along the shank; this penetrates at depths ranging from 16.5mm to 18mm in the warp with the maximum force being 34N. In the weft the peak occurs at a depth of between 17.5mm and 18.5mm, with the highest peak being smaller than the warp at 25N. In the bias, the widened shank peaked later between 19.5mm and 20mm; the most force achieved was a mere 6N. Again, the small force may have been due to the yarns being pushed apart easily due to the stretch capabilities of the fabric weave.

The section C plateau begins after 12.5mm along the weapon, where the weapon width remains constant. In the fabric in the warp, the plateau registers between 16.5-18mm penetration depth, and the force does not drop below 1.5N. In the weft, the plateau starts between 17.5-18.5mm depth and the forces remain just above 1N. In the bias the plateau begins between 15.5-17mm and the force drops to below 1N.

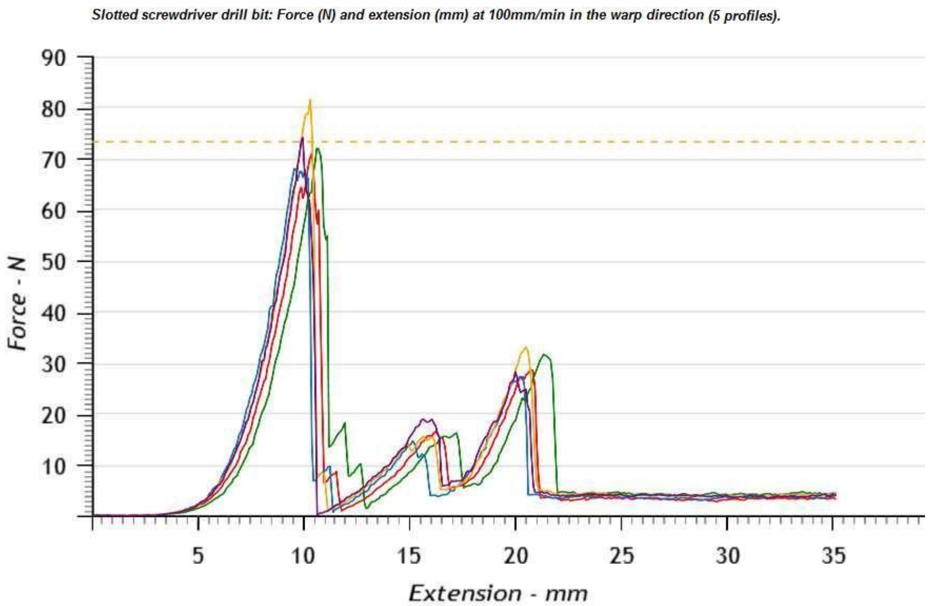


Figure 52: Weapon-force profiles (n=5) for the slotted screwdriver drill bit at 100mm/min in the warp direction. Mean maximum force is 73.22N, coefficient of variation is 6.94%.

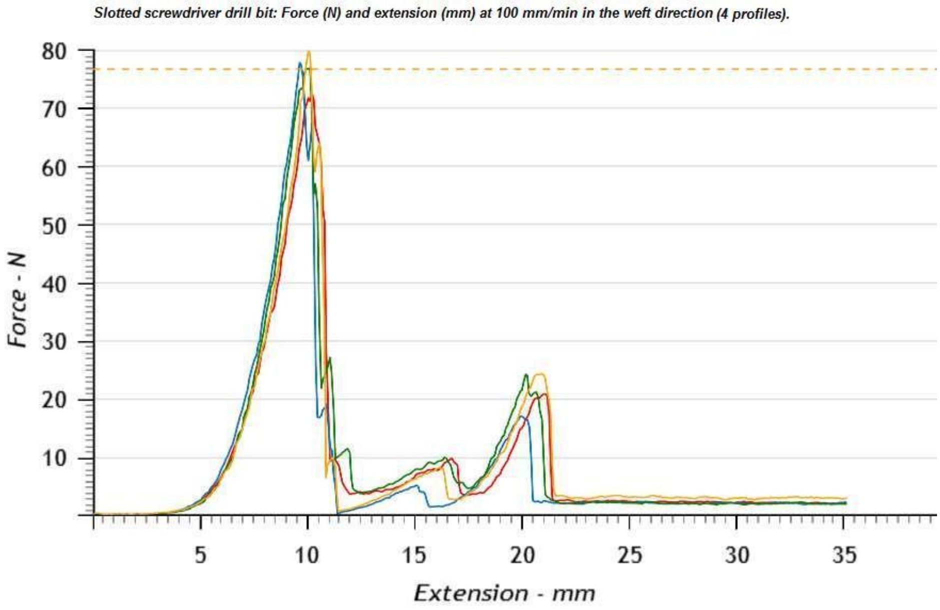


Figure 53: Weapon-force profiles (n=4) for the slotted screwdriver drill bit at 100mm/min in the weft direction. Mean maximum force is 76.63N, coefficient of variation is 4.05%.

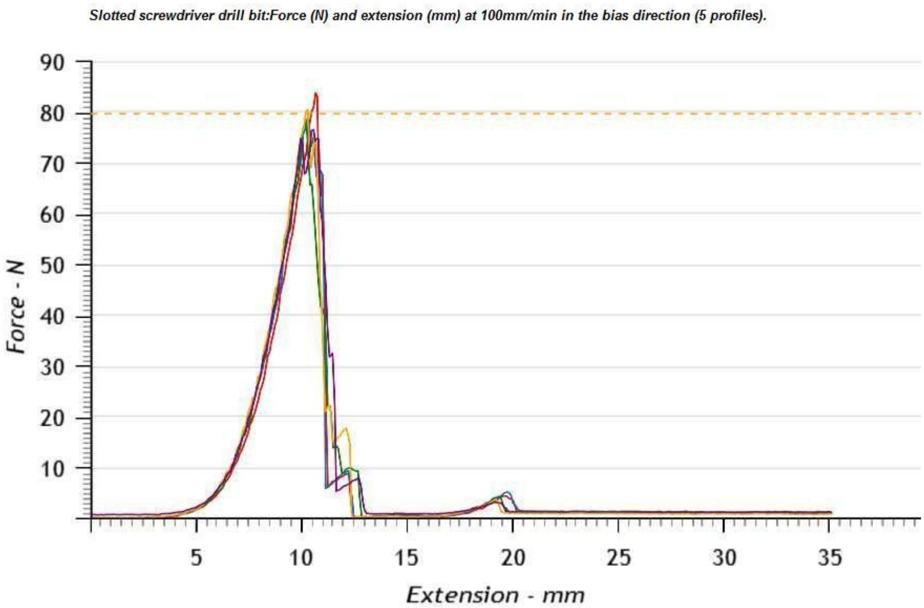


Figure 54: Weapon-force profiles (n=5) for the slotted screwdriver drill bit at 100mm/min in the bias direction. Mean maximum force is 79.54N, coefficient of variation is 3.40%.

When the combined weapon-force profiles created at 2000mm/min in the warp (figure 55), weft (figure 56) and bias directions (figure 57) are compared, the first peak appears more uniform in the warp. The lines between points on the graphs are straight with no mini peaks or waves as small changes in force are not registered at this faster speed.

For section A, the penetration depths to achieve the maximum force in the warp and weft are both between 8mm and 9.5mm. In the bias these maximum forces occurred earlier at between 6.5mm and 8mm.

For section B, if this was a regular screwdriver, no further forces would peak as the shank would be narrower than the blade. As this was a screwdriver drill bit, there is a further registering of force due to its shape, although there is no clear registering of the force as the screwdriver blade section of the weapon penetrated the fabric as in the warp and weft at the slower speed. The final peak is where the weapon width widens further at 12.5mm along the shank; this penetrates at depths ranging from 18.5mm to 20.5mm in the warp with the maximum force being 19.5N. In the weft the peak occurs at a depth of between 19.5mm and 20mm, with the highest peak being smaller than the warp at 14N. In the bias, the widened shank peaked earlier at 18mm; the most force achieved was the same as the slower speed – a low 6N.

The section C plateau begins after 12.5mm along the weapon, where the weapon width remains constant. In the fabric in the warp, the plateau commences between 22mm and 23mm penetration depth, and the forces range from 2.5N to 5N. In the weft, the plateau starts between 21.5mm and 24.5mm depth and the forces range between 1.5N and 4N. In the bias the plateau begins at 20.5mm for all samples force remain between 0.5N and 1.5N.

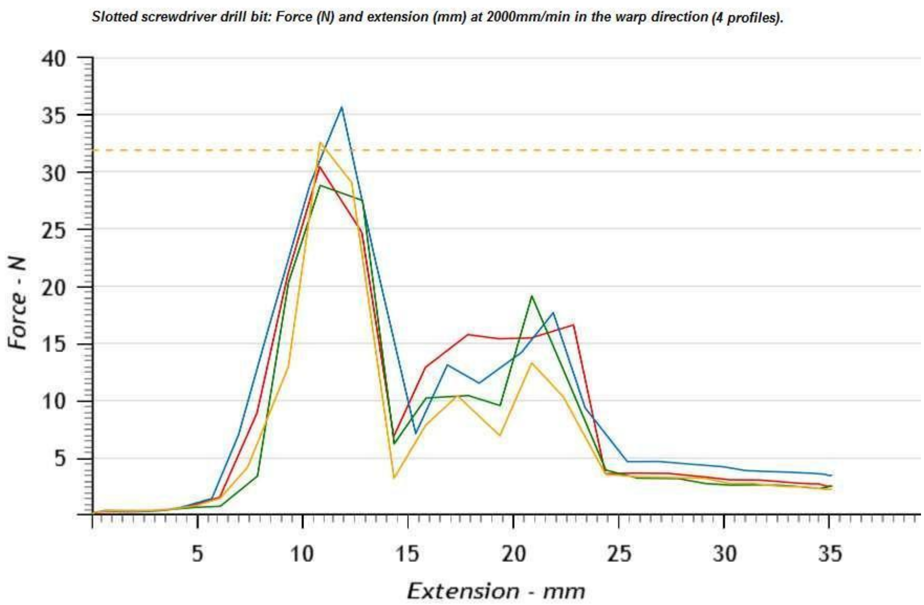


Figure 55: Weapon-force profiles (n=4) for the slotted screwdriver drill bit at 2000mm/min in the warp direction. Mean maximum force is 31.80N, coefficient of variation is 9.32%.

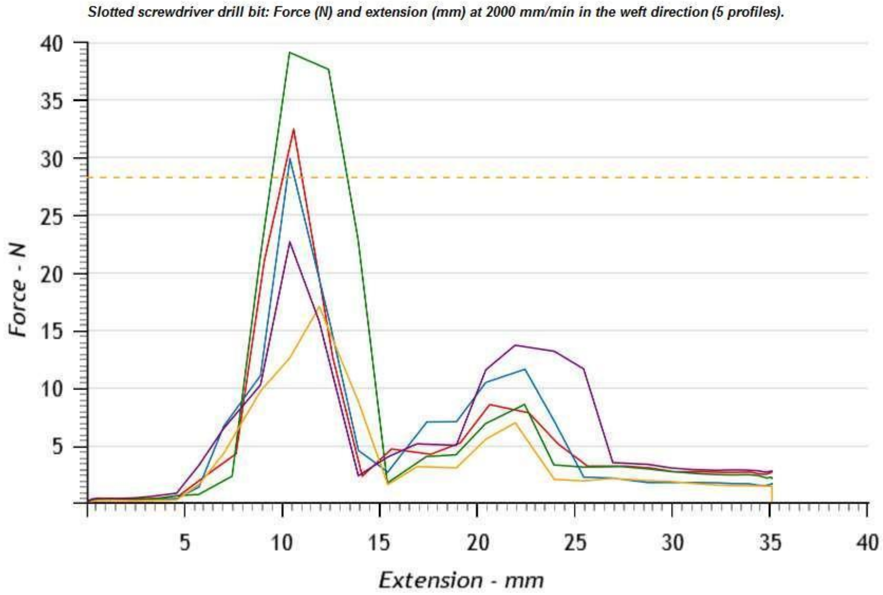


Figure 56: Weapon-force profiles (n=5) for the slotted screwdriver drill bit at 2000mm/min in the weft direction. Mean maximum force is 28.18N, coefficient of variation is 30.47%.

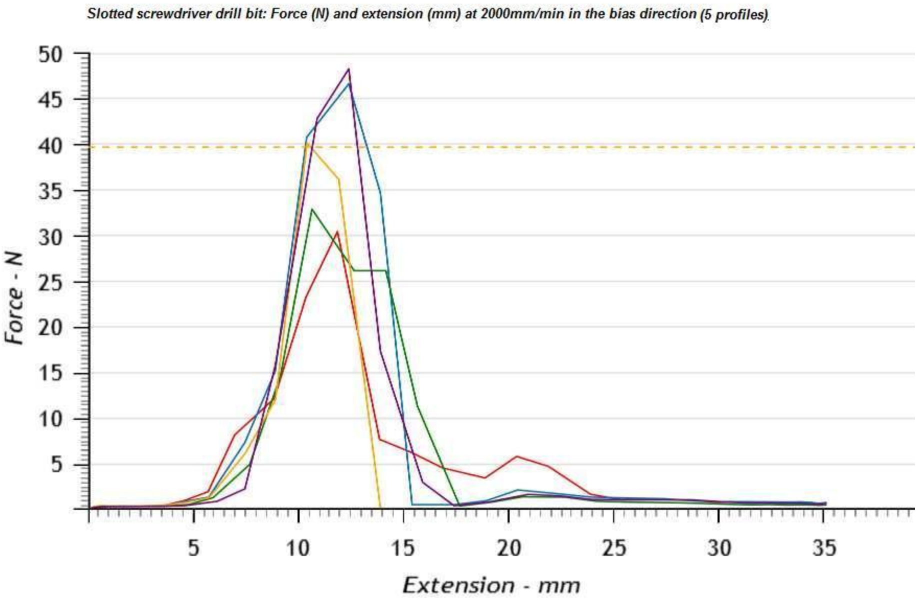


Figure 57: Weapon-force profiles (n=5) for the slotted screwdriver drill bit at 2000mm/min in the bias direction. Mean maximum force is 39.58N, coefficient of variation is 20.13%.

Weapon-force profiles were created into paper (figure 58) at 100mm/min as a non-woven medium for comparison with a woven fabric. The CV was higher than anticipated at 13.82%; this displays much variation. It displays a similar shaped profile to the warp and weft at 100mm/min.

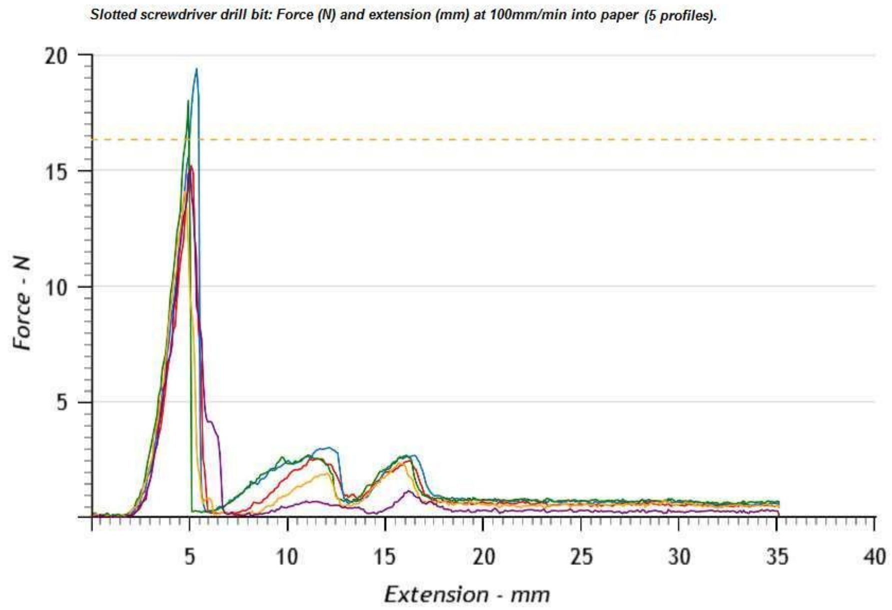


Figure 58: Weapon-force profiles (n=5) for the slotted screwdriver drill bit at 100mm/min into paper. Mean maximum force is 16.30N, coefficient of variation is 13.82%.

A box plot graph was created to compare the distribution of maximum peak forces (figure 59). The most obvious difference is between speeds as the 2 groups of data are completely separate. When comparing directions within the same speeds, there is an overlap of data in every direction which shows that some maximum forces can be achieved in each direction.

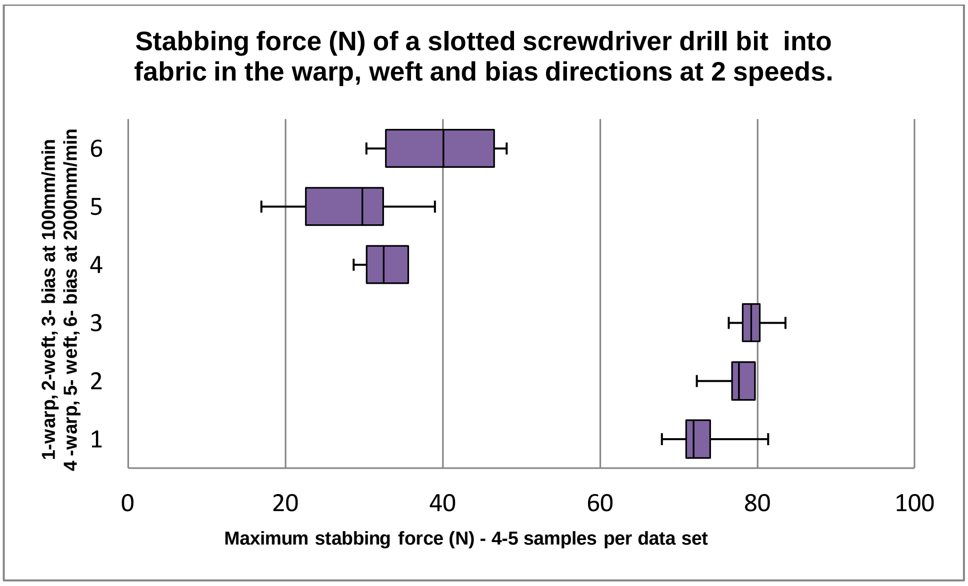


Figure 59: Maximum forces achieved for the slotted screwdriver drill bit in the warp, weft and bias directions at 2 speeds into fabric.

3.2.6 Crosshead screwdriver drill bit

Five tests instead of 7 were carried out for this weapon; the weft was not necessary as the cross of the tip aligned with the warp and weft simultaneously. Due to mounting difficulties in the machine, the drill bit rotated slightly and was tested at a slight bias (figure 60). It is expected that the results between the directions are similar due to there being less contrast in direction. The punctures in the warp direction samples had an overall square appearance and the bias resulted in a rectangular diamond. These shapes reflect the weapon head shape as oppose to the hexagonal shaft. The full test reports can be seen in appendices 36-40.

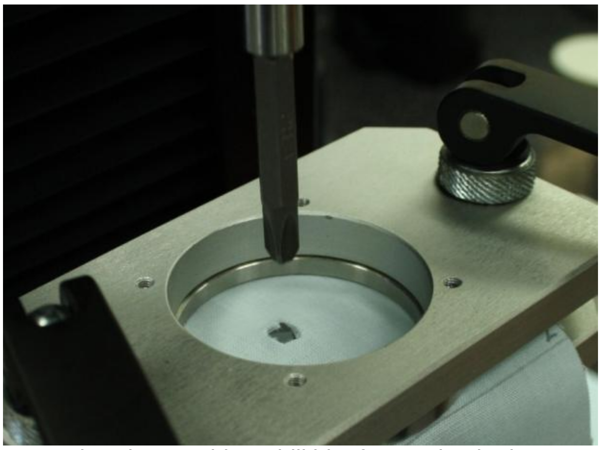


Figure 60: Crosshead screwdriver drill bit after testing in the warp direction.

When the combined weapon-force profiles created at 100mm/min in the warp (figure 61) and bias directions (figure 62) are compared, the overall shapes for both graphs are similar in appearance and the results overlay one another closely. The CV of 1.58% in the warp is the lowest CV achieved in this study.

For section A in both the warp and bias, it takes a range of 6.5-7mm of penetration for the fabric to puncture.

During section B, both tests – warp and weft - drop away to a trough at less than 1N within the next 0.5mm of penetration. This is due to the weapon narrowing behind the head. For a regular screwdriver where the shank continues to be narrower, there would be no other force registered. As this is a screwdriver drill bit, there is a further registering of force: a gentle slope is recorded which is more pronounced in the warp direction, until the obvious change in the width at 13mm along the shank of the weapon. The profiles display this second peak at a depth range of 15.5mm - 16.5mm for the warp, and 16.5mm – 17mm in the bias. The force ranges differ slightly at 30-40N in the warp and 25-33N in the bias.

The section C plateau begins along the weapon at 13mm, where the width remains constant and the force again drops to below 1N. This is displayed on the weapon force profiles at 17mm – 17.5mm weapon depth in the warp direction, and 16.5mm – 17.5mm in the bias.

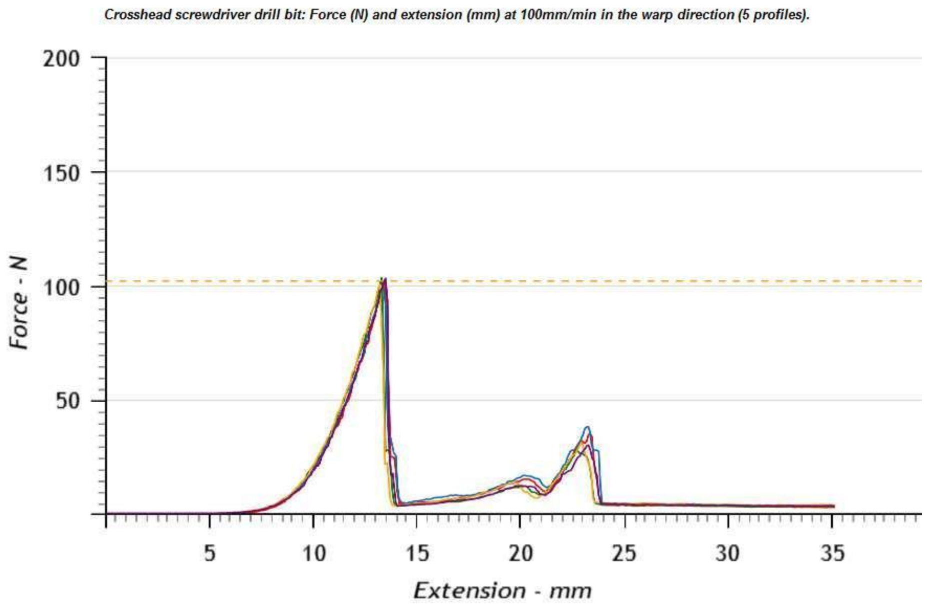


Figure 61: Weapon-force profiles (n=5) for the crosshead screwdriver drill bit at 100mm/min in the warp direction. Mean maximum force is 101.63N, coefficient of variation is 1.58%.

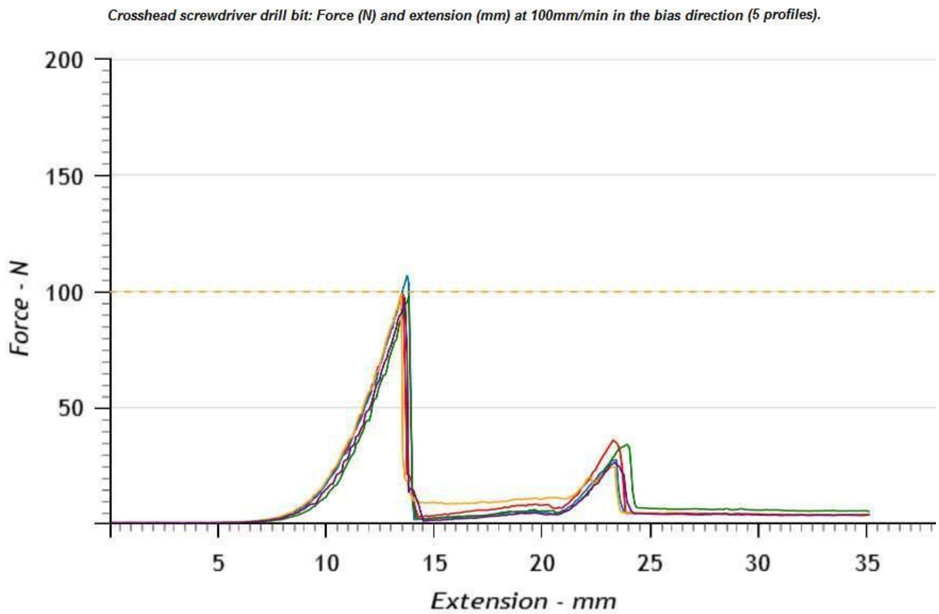


Figure 62: Weapon-force profiles (n=5) for the crosshead screwdriver drill bit at 100mm/min in the bias direction. Mean maximum force is 99.50N, coefficient of variation is 3.92%.

When the weapon-force profiles created in the warp (figure 63) and bias directions (figure 64) at 2000mm/min are compared, the overall shapes are similar but vary more than at a slower speed. Both of the mean force values are less than half those at 100mm/min.

For section A in the warp it takes a range of 5-6.5mm of penetration for the fabric to puncture. In the bias, the weapon travels a range of 6.5mm – 8.5mm before the fabrics punctures.

During section B, in the warp the force drops away to a range of 2.5N – 6N over next 0.5mm of penetration. In the bias, the force drops to a range of 2N – 6N over a range of 3mm penetration. At this point for both directions at 100mm/min, the force dropped to <1N. The gentle slope recorded at 100mm/min is unobservable. The profiles display a second peak where the weapon widens at 13mm along the shank; this penetrates at depths ranging from 15mm to 16.5mm for the warp with a range of forces from 13N – 18.5N. The bias yielded much more variable results: the penetration depths ranged from 16.5mm – 18.5mm and forces ranged from 9.5N - 22N.

The section C plateau begins at 13mm for the weapon, where weapon width remains constant and the force drops to below 1N. In the warp the plateau begins at a range of depths from 18.5mm – 22.5mm. In the bias the weapon starts to plateau over a 2.5mm range, from 20mm.

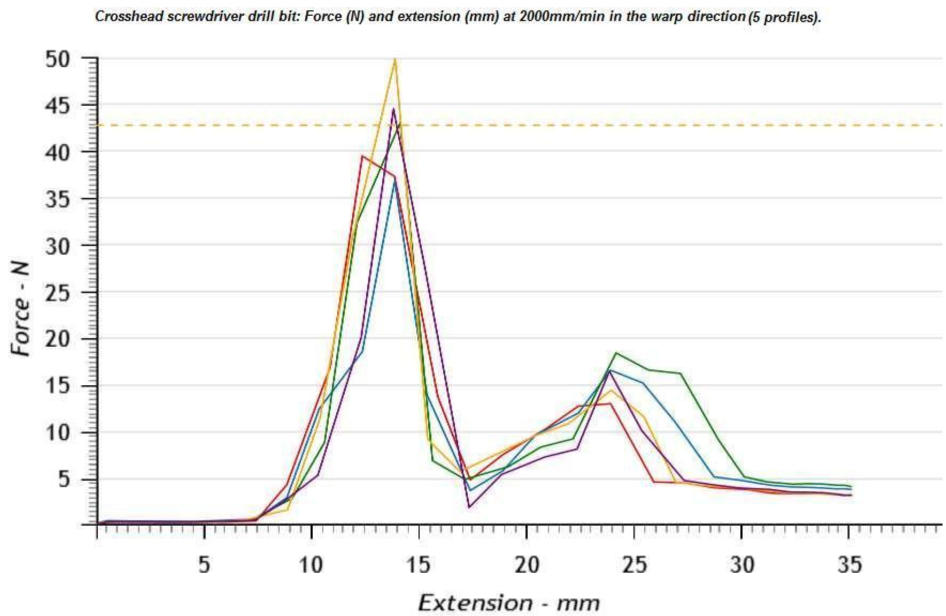


Figure 63: Weapon-force profiles (n=5) for the crosshead screwdriver drill bit at 2000mm/min in the warp direction. Mean maximum force is 42.67N, coefficient of variation is 11.73%.

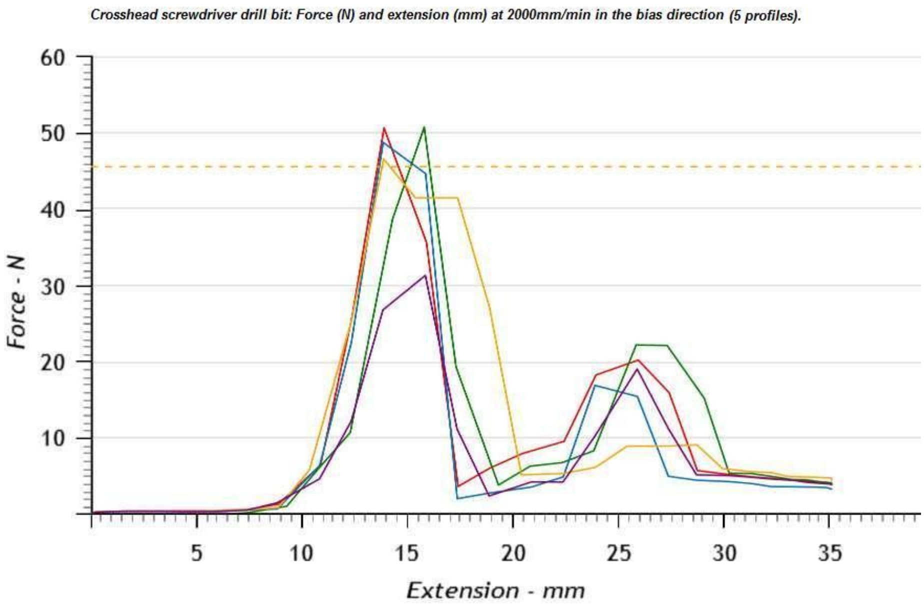


Figure 64: Weapon-force profiles (n=5) for the crosshead screwdriver drill bit at 2000mm/min in the bias direction. Mean maximum force is 45.48N, coefficient of variation is 17.97%.

Weapon-force profiles were created into paper (figure 65) at 100mm/min as a non-woven medium for comparison with a woven fabric. The CV was greater than expected at 21.55%. It displays features closer to those seen in the warp at the same speed.

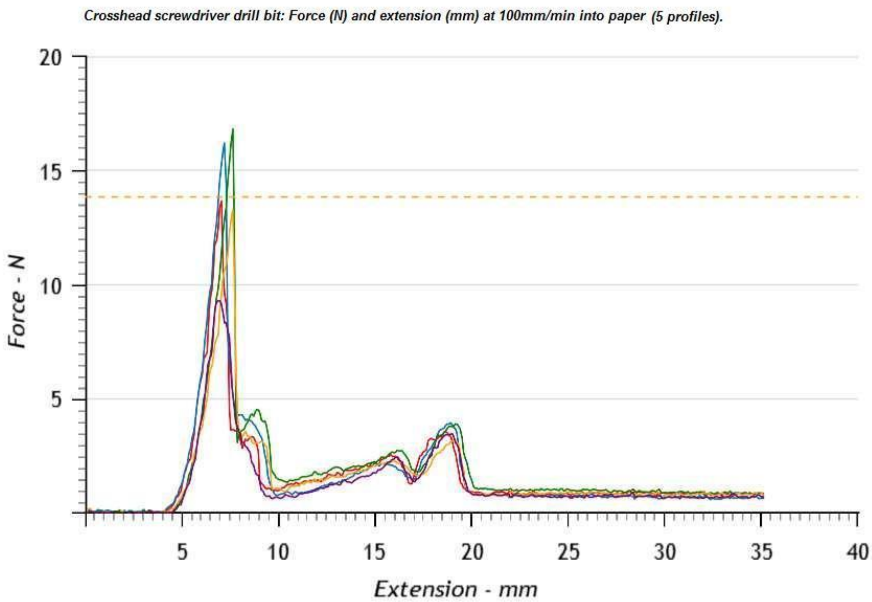


Figure 65: Weapon-force profiles (n=5) for the crosshead screwdriver drill bit at 100mm/min into paper. Mean maximum force is 13.81N, coefficient of variation is 21.55%.

A box plot graph was created to compare the distribution of maximum peak forces (figure 66). The most obvious difference is between speeds; the 2 groups of data are completely separate. When comparing directions within the same speeds, there is an overlap of data which shows that some of the maximum forces can be achieved in both directions.

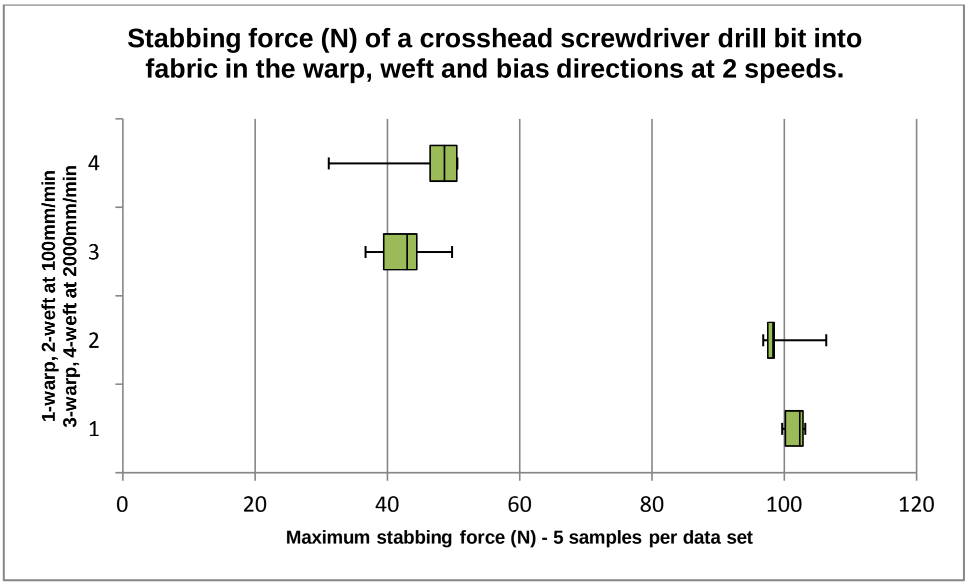


Figure 66: Maximum forces achieved for the crosshead screwdriver drill bit in the warp, weft and bias directions at 2 speeds into fabric.

3.3 Stab force comparisons

The stab force profiles revealed that in some cases, the maximum peak force achieved was not always the first puncture; it could occur as late as the 4th peak (breadknife) indicating that the weapon pushed against the yarns before the force peaked followed by the yarn rupturing and the weapon penetrating. The penetration depths for the maximum peak forces proved to be consistent (within 0.5mm) regardless of whether the maximum force was the first peak, or even if it had a high CV. Section B on the profiles reflected the shape of the weapon from maximum force at the tip to reaching full width. For the 3 sharpest knives into paper, the overall shape was created through mini peaks as the weapon pushed through and small fluctuations were recorded. A 100mm/min in the fabric, as the weapon moved through, these mini peaks were more pronounced as the severing of yarns were recorded. At the faster speed of 2000mm/min, the fluctuations remain but are reduced in number. For the 2 screwdriver drill bits, the lines created are slightly wavy at the slower speed, which turn to long angular lines at the faster speed. The breadknife has many peaks throughout its shape which are caused by the teeth, but are not seen on the graphs at a faster speed. The plateau at the latter part of the profiles ranged from almost zero Newtons (double edged blade warp 2000mm/min) to 6N (breadknife 2000mm/min); this measurement was dependant on the rate of the widening of the blade.

A summary of the mean maximum forces are shown in table 6 below. The single edged blade with a curved spine achieved the lowest mean maximum force (bias; the crosshead screwdriver drill bit (warp) achieved the highest mean maximum force. Before these mean results were disseminated any further, the validity of reporting the mean result required verifying through examination of the coefficients of variations (CVs).

Mean Max force (N)	**100mm/min**								**2000mm/min**					
See appx for full data	**paper**	appx	**warp**	appx	**weft**	appx	**bias**	appx	**warp**	appx	**weft**	appx	**bias**	appx
Breadknife	7.83	7	41.07	1	52.47	3	45.42	5	28.37	2	37.37	4	33.37	6
Single edged blade straight spine	3.87	14	12.21	8	18.43	10	10.67	12	9.02	9	6.8	11	9.5	13
Single edged blade curved spine	4.5	21	12.2	15	14.92	17	15.9	19	7.38	16	6.48	18	6.36	20
Double edged blade	3.85	28	12.78	22	15.58	24	17.5	26	6.72	23	6.45	25	8.52	27
slotted head screwdriver drill bit	16.3	35	73.22	29	76.63	31	79.54	33	31.8	30	28.18	32	39.58	34
crosshead screwdriver drill bit	13.81	40	101.63	36			99.5	38	42.67	37			45.48	39

Table 6: The mean maximum force data for each weapon, direction and speed.
Full data is available in the appendix – see number next to mean.

It was expected that the paper would display little variation and that comparison with the fabric would highlight the effect of the plain weave on the force required for a weapon to penetrate. The stab cuts made into paper with the 6 weapons produced coefficient of variations from 5% to 21.55% (table 6); results below 3% indicate consistent behaviour. The paper was considered too variable so the paper was disregarded for any further force comparisons.

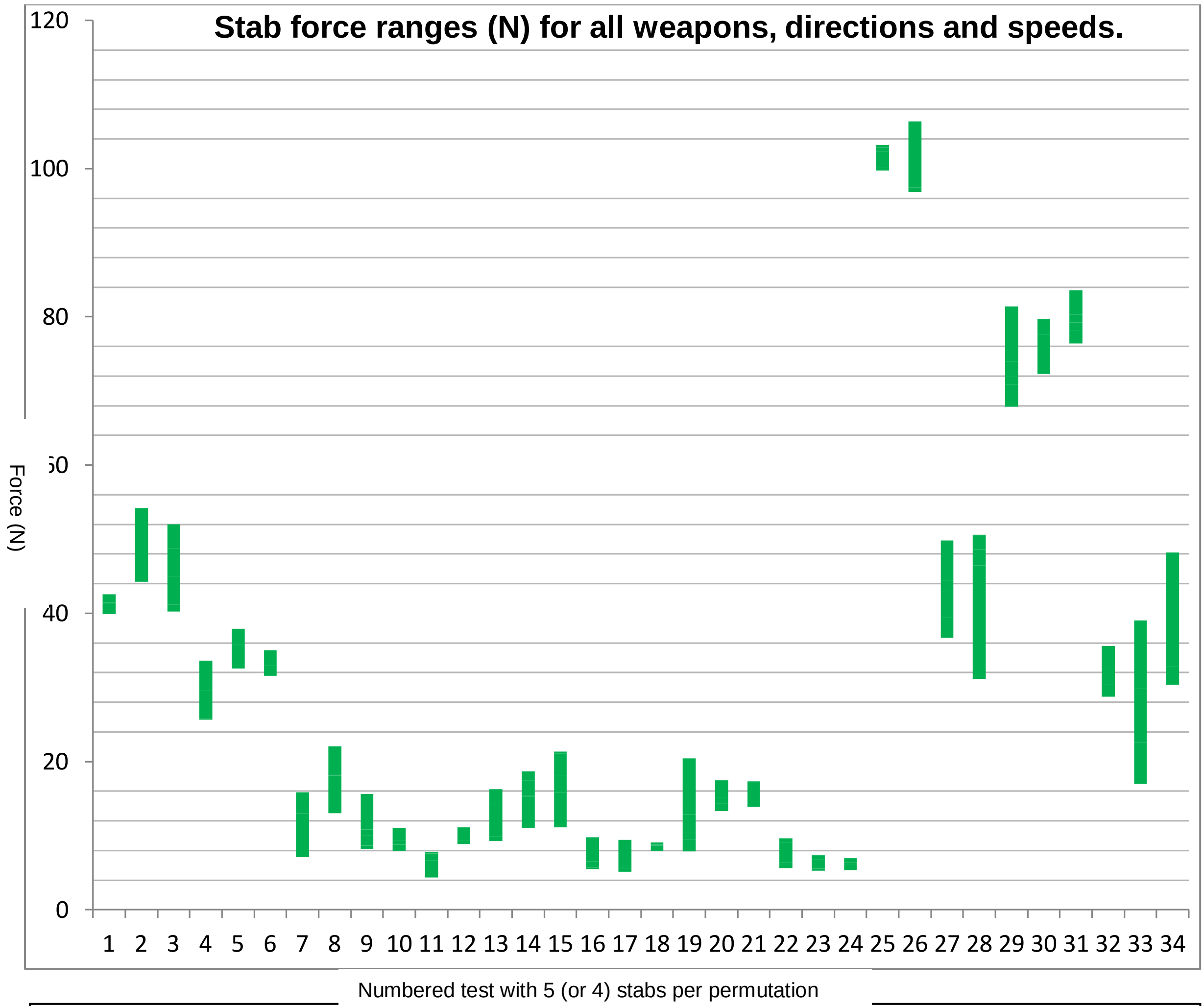
Direction	**Paper**	**Warp**	**Warp**	**Weft**	**Weft**	**Bias**	**Bias**
Speed (mm/min)	**100**	**100**	**2000**	**100**	**2000**	**100**	**2000**
Bread knife	8.95	2.72	11.76	9.67	6.21	10.94	3.78
Single edged blade with a straight spine	14.81	25.82	14.08	18.67	20.93	27.85	9.78
Single edged blade with a curved spine	14.77	40.55	24.94	10.68	15.14	10.10	10.31
Double edged blade	5.00	23.75	26.22	18.61	26.41	24.15	5.74
Slotted head screwdriver drill bit	13.82	6.94	9.32	4.05	30.47	3.40	20.13
Cross head screwdriver drill bit	21.55	1.58	11.73			3.92	17.97

Table 7: Coefficients of variation (%) for the maximum stab force data sets in fabric and paper. The crosshead screwdriver drill bit has no weft samples as the weapon lines up with the warp and weft simultaneously.

A summary of the CVs for the maximum peak forces for each weapon at both speeds into fabric can also be seen in table 7. CVs for all the fabric range from 1.58% – 40.57% which is visually displayed in the weapon-force profiles. Only 2 weapons had low CVs (<3%) and both of these occurred in the warp direction at 100mm/min but with very different mean maximum forces: the breadknife (2.72%, 41.07N) and the cross head screwdriver drill bit (1.58%, 101.63N). All the other data sets were more variable with higher CVs, including the four permutations with only 4 tests (underlined in table 7). Although the small data sets for each permutation were adequate according to textile testing methods, a larger data set would have presented a more robust argument.

As the CVs for the fabric tensile strength tests were extremely low (table 1), the variation of the stabbing forces is more likely to be due to the action of the weapons on the fabric, and not variability within the fabric structure. The variation in maximum forces reflects how the blade tip interacts with the fabric – whether it pushes between the yarns or directly onto a yarn.

With such variability of results, it would be misleading to report the mean force value when answering the forensic question ‘How much force was involved in the stabbing?’ The graphs at the end of each section have shown the variation of the results within each weapon and how the direction affects the maximum forces. Comparisons are now drawn between each weapon at both speeds in all directions (figure 67).



1-6: Breadknife
1. Warp 100 mm/min
2. Weft 100 mm/min
3. Bias 100 mm/min
4. Warp 2000 mm/min
5. Weft 2000 mm/min
6. Bias 2000mm/min

7- 12: Single edged blade with a straight spine
7. Warp 100 mm/min
8. Weft 100 mm/min
9. Bias 100 mm/min
10. Warp 2000 mm/min
11. Weft 2000 mm/min
12. Bias 2000 mm/min

13-18: Single edged blade with a curved spine
13. Warp 100 m/min
14. Weft 100mm/min
15. Bias 100 mm/min
16. Warp 2000 mm/min
17. Weft 2000 mm/min
18. Bias 2000 mm/min

19-24: Double edged blade
19. Warp 100 mm/min
20. Weft 100 mm/min
21. Bias 100 mm/min
22. Warp 2000 mm/min
23. Weft 2000 mm/min
24. Bias 2000 mm/min

25-28: Crosshead screwdriver drill bit
25. Warp 100 mm/min
26. Bias 100 mm/min
27. Warp 2000 mm/min
28. Bias 2000 mm/min

29-34: Slotted head screwdriver drill bit
29. Warp 100 mm/min
30. Weft 100 mm/min
31. Bias 100 mm/min
32. Warp 2000 mm/min
33. Weft 2000 mm/min
34. Bias 2000 mm/min

Figure 67: Comparison of all maximum stab force data for each weapon, direction and speed.

Figure 67 demonstrates the distribution of all data and the range of maximum forces achieved for each permutation. For each screwdriver at 100mm/min (numbers 25-26 & 29-31), the 2 groups of directional data are isolated, although there is a complete overlap within each group; this indicates that the direction of the weapon to the fabric has little influence on the forces at this slow speed. A larger data set may have revealed whether these 2 groups would have remained isolated. At 2000mm/min, both screwdrivers fall mainly within the same broad range as the breadknife data (numbers 1-6). Even with a small sample size, enough data was produced to reveal that it is possible for the slotted head screwdriver to produce overlapping data (test 33) with the 3 sharp knives - weapons of very different morphologies (6 tests), suggesting that the tip radius is not always the most influential factor.

The minimum force required to stab this particular fabric at 100mm/mm is achieved in the warp direction (cutting of the weft yarns) for 5 of 6 weapons (figure 67, table 8). The warp direction contains less dense weft yarns at 25 per 10mm and this may contribute to easier penetration in this direction, as the weft direction contains denser warp yarns at 30 yarns per 10mm. The smallest force achieved was with the single edged blade with a straight spine (table 2, no. 2); the tip of this weapon has a small radius visually which pushed the yarns apart resulting in a low peak force; it glided in gently as the blade cut through the yarns. The same knife also has the highest maximum force of the 3 sharp blades; it was observed pushing down on a yarn which had to be severed through pushing as oppose to slicing through the yarn. The cross head screwdriver did not line up exactly with the warp and so was slightly on the bias. If we remove this due to testing errors, then it can be stated that the smallest force required for each weapon when stabbed into this fabric at 100mm/min occurs in the warp direction. The maximum force at 100mm/min reveals no directional pattern.

Weapon at 100mm/min	**Min force (N)**	**Direction**	**Max force (N)**	**Direction**	**Range (N)**
Single edged blade with a straight spine	7.14	warp	22.06	weft	14.92
Single edged blade with a curved spine	7.91	warp	20.47	warp	12.56
Double edged blade	9.3	warp	21.06	bias	11.76
Bread knife	39.88	warp	54.17	weft	14.29
Slotted head screwdriver drill bit	67.91	warp	83.62	bias	15.71
Cross head screwdriver drill bit	96.85	bias	106.38	bias	9.53

Table 8: The minimum and maximum forces (N) including the directions and range for each weapon at 100mm/min, presented in order of increasing minimum force.

When examining the minimum force required to stab this particular fabric at 2000mm/min, for 4 out of 6 weapons, this occurs in the weft direction (table 9). This is in contrast to 100mm/min, and so at the faster speed, the yarn density has no effect. The maximum forces do not follow the same pattern – again, the single edged blade with a straight spine has both the lowest and highest forces of the 'sharper' weapons. The maximum force at 2000mm/min reveals no directional pattern.

Weapon at 2000mm/min	Min force (N)	Direction	Max force (N)	Direction	Range (N)
Single edged blade with a straight spine	4.39	weft	11.13	bias	6.74
Double edged blade	5.15	weft	9.79	warp	4.64
Single edged blade with a curved spine	5.29	weft	9.65	warp	4.36
Slotted head screwdriver drill bit	17.00	weft	48.18	bias	31.18
Bread knife	25.63	warp	37.89	weft	12.26
Cross head screwdriver drill bit	31.18	bias	50.62	bias	19.44

Table 9: The minimum and maximum forces (N) including the directions and range for each weapon at 200mm/min, presented in order of increasing minimum force.

When comparing the range of results for each weapon between the 2 speeds, as the speed increases, the range of results for the 3 sharp knives decrease. In contrast, the range of forces for both screwdriver drill bits approximately doubles, and there is little difference between the 2 speeds for the breadknife (tables 8 & 9).

3.4 Stab cut length

The stab cuts in the warp, weft and bias directions at 2 speeds for each of the 4 blades were measured end to end in a straight line to the nearest 0.5mm, and the mean values were expressed as a percentage of the blade width (table 10). The warp direction samples are a record of the severance of the weft threads and the weft results are a record of the severance of the warp threads. Paper was stabbed at 100mm/min for comparison. The coefficient of variation (CV) was calculated for each permutation to identify variability of the stab cuts in the warp, weft and bias directions whilst stabbed in a control manner. Full data can be seen in appendix 41. For each set of cut length results, the CV was consistently below 3%; this indicates that the stab cuts were repeatable and reliable. These figures are examined here in conjunction with the results from the extension test. The mean extensions were found to be 11.25mm in the warp direction, 15.42mm in the weft and 34.53mm in the bias.

	Blade type	**Bread knife**		**Single edged straight spine**		**Single edged curved spine**		**Double edged**	
	Maximum blade width	**25mm**		**18.5mm**		**19.5mm**		**24mm**	
	Speed mm/min	**100**	**2000**	**100**	**2000**	**100**	**2000**	**100**	**2000**
Warp	Mean	23.00	23.00	18.00	18.20	19.90	20.50	23.13	23.00
	Cut as a % of blade width	92.00	92.00	97.30	98.38	102.05	105.13	96.35	95.83
	CV	0	0	1.96	1.50	1.12	2.44	1.08	2.66
Weft	Mean	22.60	22.60	17.50	17.90	19.50	19.80	23.2	23.00
	Cut as a % of blade width	90.40	90.40	94.59	96.76	100.00	101.54	96.67	95.83
	CV	0.99	1.85	2.02	1.25	0	1.38	1.18	1.54
Bias	Mean	22.50	21.90	17.50	17.50	18.60	19.40	22.5	22.70
	Cut as a % of blade width	90	87.60	94.59	94.59	95.38	99.49	93.75	94.58
	CV	1.57	2.50	0	0	2.94	1.15	1.57	2.51
Paper	Mean	25.10		19.70		20.50		24.4	
	Cut as a % of blade width	100.40		106.49		105.13		101.67	
	CV	2.60		2.27		0		0.92	

Table 10: Mean cut lengths in the warp, weft and bias directions, the stab cut lengths expressed as a percentage of the blade width and the coefficient of variation for the 4 blade types.

The stab cuts created in paper displayed stab cut lengths that were greater than the blade width for all 4 blades (CV <3%). This may be partly due to the paper and knife being stationary and the paper having little or no stretch. There are two possible reason for this outcome; either the back of the knife curved backwards (breadknife), or knife may not have been perfectly perpendicular, which was only apparent after testing.

There were 4 other permutations where the cut length was the same as or wider than the blade width: these were all made by the single edged blade with the curved spine in the warp and weft directions at both speeds. During testing, the spine of this knife was observed pushing against and tearing the side of the stab cut as it travelled through the fabric. In the bias at both speeds, the cut length was less than the blade width, although the knife had not been moved. This can be explained by the yarns moving apart to accommodate the knife with the fabric stretching around the spine; this is supported by the fabric extension test results showing more stretch in this direction than in the warp or weft.

For the remaining results, without exception, the mean cut lengths are shorter than the maximum blade widths. Also, in every case, the bias cuts are always shorter than both the warp and the weft cuts. These results are not intended to reflect real scenarios but provide a controlled environment where the interaction of weapons on a plain fabric can be examined. The fabric weave accommodates the blade by the yarns moving apart and avoids being severed to the full width of the blade.

The conclusions for stab force are presented in chapter 5.

Chapter 4: Weathering by outdoor exposure results and discussion

It is well established in forensic literature that it is possible to identify the type of weapon used in a crime through the examination of the damage morphology created in textiles. The purpose is to aid police in their investigation by providing details about the weapon involved. Alteration of this textile damage through any means is less well researched, yet knowledge of the effects of weathering on damaged and undamaged clothing is essential if the forensic practitioner is to analyse clothing effectively. Even before the garment is submitted for forensic analysis, the individual responsible for choosing which items will be analysed for the case will make decisions based on their knowledge of their usefulness. The purpose of this experiment is to explore whether the examination of clothing damage which has been exposed to the elements before discovery would be a valid choice. Methods involve both subjective observation and objective measurements with statistical analysis, with the aim to discover if the two methods complement one another. No other similar research has been carried out.

4.1 Experimental design

There are 2 hypotheses for this research. The experiment was created to determine if weathering alters the severance morphology of knife stab cuts in clothing, which may thwart identification of the weapon. The extent of alteration will be explored through cut length modification and comparisons will be made between the type of knife, the direction of the stab cut, and the length of exposure.

The first set of objectives took place before weathering. The stab cuts were examined to determine if the weapon could be identified. The yarn snag frequency, shape and stab cut length was recorded. T-test analysis determined any significant differences between the 2 directions for each blade.

Secondly, after weathering, any changes in thickness were noted. The cuts were examined to see if the weapon type could still be identified. The stab cut length was re-measured in a straight line to the nearest 0.5mm. Paired t-test analysis was carried out to identify any statistically significant differences (where $P<0.05$) between the stab cut lengths (n=5) before and after weathering by outdoor exposure. These differences were analysed to identify any patterns in the results regarding knife type, stab cut direction and length of exposure.

4.2 Observations before weathering

Each stab cut was photographed for comparative purposes, and visually examined to determine whether the severance morphology of the stab cut reflected the weapon type. It was evident that manually stabbing into a polystyrene block resulted in an array of stab cuts shapes with both single and multiple cuts of differing lengths (figure 68). The multiple cuts were created through the fabric folding into the cut as the stab was applied, or during withdrawal of the weapon.

There is much controversy over which skin simulant ought to be used when researching stabbing. Polystyrene was chosen for creating the stab cuts for weathering as it has been proven to be the most reliable material for reproducible results [62]. It could be argued that the stab cuts ought to have been more regular for comparative purposes by being applied in a more controlled manner; this could have been achieved by utilising the same machinery used to produce the stab force data - Titan[4]. The variety reflects real life scenarios and gave rise to the opportunity to explore any patterns within randomly applied stab cuts.

The cut lengths were recorded and will be discussed in the data sections. Full sets of original data can be seen in appendices 42 & 43. Human error must always be considered when measuring. Fortunately, as having been repeatedly accredited by Precision Processes Textiles, this fact may invoke confidence in the results.

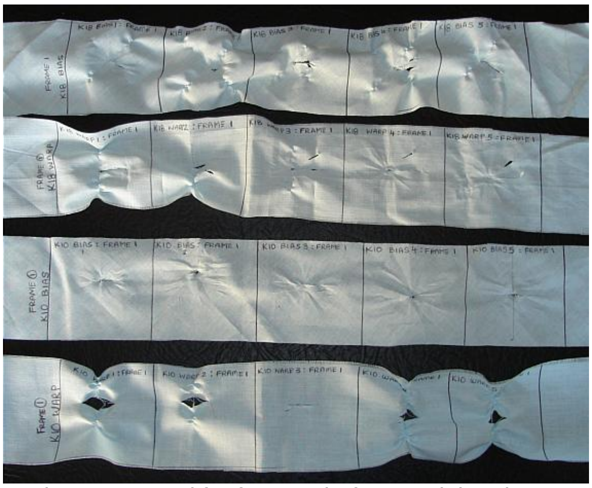


Figure 68: All 20 stab cuts created for frame 1 before straightening or outdoor exposure.

When a yarn was snagged by the knife point, it was pushed into the stab cut. Where this occurred, the fabric was straightened outwardly from the cut, leaving the yarn in situ. This was essential to enable measurements to be taken, but it also preserved the yarn intake. All 60 stab cuts shapes were analysed before weathering and 6 distinct stab cut shapes were identified; a summary of which can be seen in table 11.

4.2.1 Stab cuts applied with a double edged blade

Stab cuts applied to this particular woven fabric with the double edged blade were identified by the neat severance of yarns at the extremities of the cut with each end finishing in a point. The point of entry for the blade tip was identified by creases in the cloth, snagged yarns pushed into the cut, or by the frayed yarn ends within the edged of the cut. It was possible to identify the double edged blade in both the warp and bias directions before outdoor exposure using these guidelines, although the frequencies of severance morphology shapes differed between these 2 sets of stab cuts.

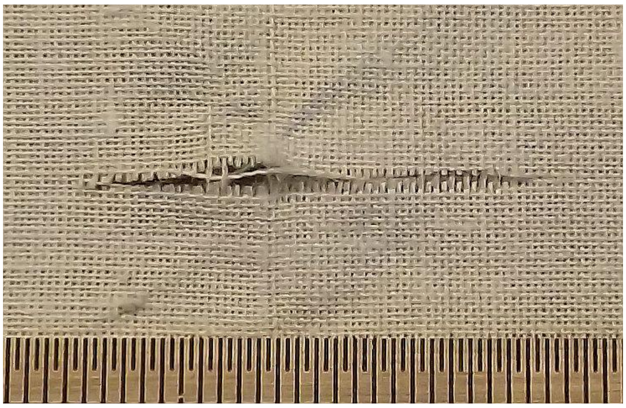


Figure 69: Before outdoor exposure – stab cut created with a double edged blade in line with the warp. Scale: each complete division = 1mm.

From the 15 stab cuts created in line with the warp, 11 were straight and stayed in line with the warp. They were neat in appearance, with little central damage (figure 69). The remaining 4 cuts consisted of subtle deviations from the straight line - a curve, a zig-zag and 2 waves (table 11).

In contrast, there were no straight stab cuts in the bias direction (figure 70). The most frequent stab cut shapes in the bias direction were waves (n=9), then curves (n=5) and one v shaped cut (table 11). The knife point damaged the yarns - this resulted in excessive fraying near the centre and easy identification.

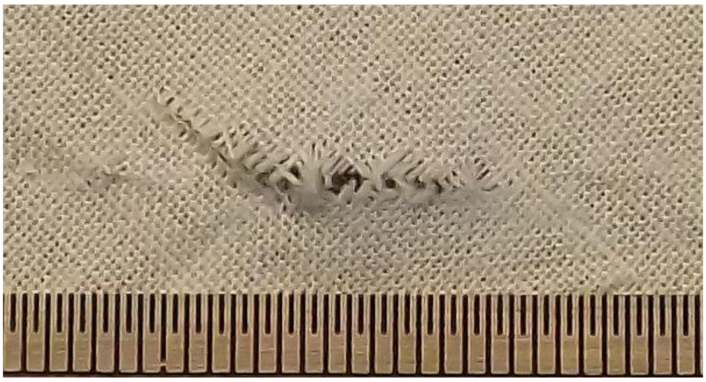


Figure 70: Before outdoor exposure – a stab cut created with a double edged blade in the bias direction. Scale: each complete division = 1mm.

Interestingly, yarn snag occurred in the majority of stab cuts in the warp (n=12) when administered with the double edged blade. In stark contrast, no stab cuts created in the bias snagged a yarn, which suggests that in this direction, the point of the knife slips between the yarns easily allowing the blade edge to cut through. One bias stab cut contained 6mm of un-severed yarns, yet the overall appearance was that of a stab cut. As only the surface of the fabric was cut it is possible that this was created as the fabric was folded into the cut and the blade slashed the surface.

4.2.2 Stab cuts applied with a single edged blade

Stab cuts applied to this particular woven fabric with a single edged blade were identified by the neat severance of yarns along the cut with one end finishing in a point at the blade edge, and the opposite having a more rounded appearance indicating where the tip punctured the fabric. Creases indicated where the tip penetrated, but also where a yarn snagged, the fabric puckered. It was possible to identify the single edged blade in both the warp and bias directions before outdoor exposure using these guidelines.

From the 15 stab cuts created in line with the warp, 12 were straight and stayed in line with the warp. They were neat in appearance, with the knife point identifiable at one end (figure 71). The remaining 3 cuts were all straight with a curved tail at the blade edge.

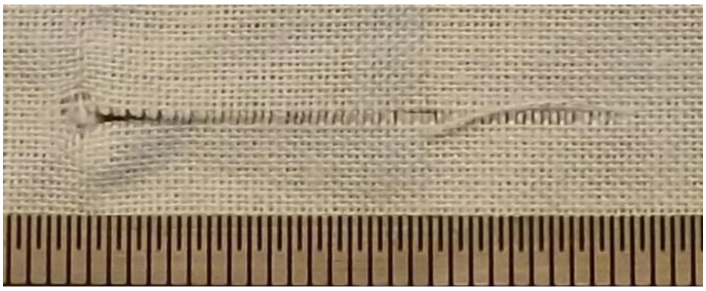


Figure 71: Before outdoor exposure: a straight stab cut in the warp direction with a single edged blade. Each complete division = 1mm.

As with the double edged blade, there were no straight stab cuts in the bias direction (figure 72) and the most frequent shapes were waves (n=11), then curves (n=3) and one v shaped cut.

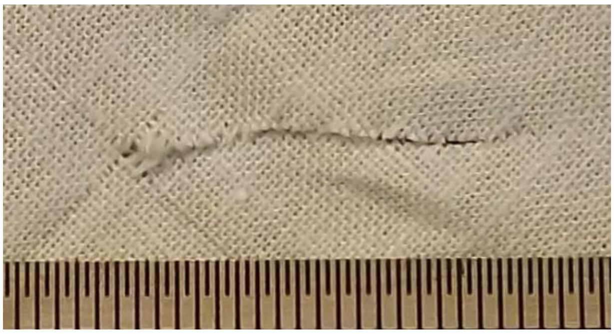


Figure 72: Before outdoor exposure: a wavy stab cut in the bias direction, created with a single edged blade. Each complete division = 1mm.

Yarn snag for stab cuts administered with the single edged blade occurred in 9 stab cuts in the warp and 13 in the bias. This is a very different pattern to the double edged blade. One bias stab cut contained 8mm of un-severed yarns, as before it is possible that this was created as the fabric was folded into the cut and the blade slashed the surface.

4.2.3 Comparisons before weathering

	Double edged blade		Single edged blade	
	Warp (n=15)	Bias (n=15)	Warp (n=15)	Bias (n=15)
Stab cut shape				
straight	11	0	12	0
straight with curved tail	0	0	3	0
curve	1	5	0	3
wave	2	9	0	11
v shape	0	1	0	1
zig zag	1	0	0	0
Yarn snag	12	0	9	13

Table 11: Summary of stab cut shape and yarn snag for all 60 stab cuts before weathering.

It was discovered that even though the stab cuts were manually administered, the majority (77%) of those intended to be in line with the warp followed the line of least resistance and produced straight cuts, regardless of weapon type. The stab cuts intended to be in the bias direction were curved, wavy and v-shaped. Even though a variety of severance morphologies were produced, the 2 different weapon types were still identifiable by using all the basic criteria for identification. Being able to identify the weapon type from the damage provided the foundation for this research.

The 2 knives were of different widths: the maximum width of the double edged knife was 24mm, and the single edged knife was 19.5mm. The 60 stab cuts resulted in a variety of lengths ranging from 8mm (achieved with both knives in the bias direction) to 32mm (single edged blade in the warp direction). This inconsistency reflects real life scenarios as the cuts were manually applied. T-test analysis showed no significant differences between directions for each blade (table 12).

Warp vs Bias	(*P* value)
Double edged blade	4.5
Single edged blade	0.06

Table 12: Statistical variation in original stab cut lengths (n=15 per permutation).
P<0.5 indicates a significant difference.

4.3 Observations and data analysis after weathering

The samples were placed near the weather station on the roof to ensure that the weather conditions recorded throughout the exposure period were relevant to the experiment. Whereas this allowed the samples to be exposed to natural conditions, it also meant that that there was no control over the conditions to which the samples were exposed, rendering this exact experiment unrepeatable. To ensure a consistent approach under known conditions, accelerated weathering testing machinery may be used. The outdoor method for this experiment was chosen as it provides real conditions and a basis on which to build.

A summary of the weather over the 8 week period is provided below to indicate the type of weather experience throughout the 8 week period (table 13). The weather is discussed further within the individual time frames, and in the summary. The full reports for February, March and April can be seen appendices 44-46.

	Temperature ºC		**Precipitation (mm) weekly average**		**Wind velocity Max (m/s)**	**Most prevailing wind direction**	**Observations**
Week commencing	**Min**	**Max**	**9:00 - 21:00**	**21:00 - 9:00**			
Week1: 26/2/13	-1.9	10.3	0.03	0	8.6	East	
Week 2: 5/3/13	-3.3	8.4	1.14	1.94	15.1	East	
Week 3: 19/3/13	-2.2	8.7	0.83	0.86	8.4	Southwest	
Week 4: 19/3/13	-1.2	7.1	1	0.2	14	East	Heavy snow drifting
Week 5: 26/3/13	-4	6.3	0.71	0.03	11	East	
Week 6: 2/4/13	-1.2	11.9	0	0	16.3	East	
Week 7: 9.4.13	2.5	16.2	0.72 (5)	1	12 (5)	East / Southwest	
Week 8: 16/4/13	1.2	16.2	0.1 (2)	1.34	11.5 (2)	Southwest	

Table 13: *A weekly summary of the 8 week exposure period 26/2/13-23/4/13. (Adapted from the weather report from the Resource Centre and Environmental Technician, University of Huddersfield).*

At the end of each weathering period, the relevant frame was brought in and left to dry. The samples were then removed, and each stab cut was compared with the 'before' photographs. Every cut was then re-measured to the nearest 0.5mm and recorded. The measurements from each frame were taken only once at the end points and then the deterioration of the samples were compared with one another. As the stab cuts were not measured at intervals leading up to the end point, it remains unclear at which point in time the sample achieved that state. This was considered at the experimental design stage, but the method used was chosen to minimalize alteration through manual handling.

4.3.1 After 1 week: frame 1

Throughout the first week, all the samples were exposed to a range of temperatures from -1.9^0 to 10.3^0 Celsius. There was little rainfall; the most that fell on one day was recorded at 0.2mm, resulting in the weekly average of 0.03mm. The maximum wind velocity throughout the week was recorded at 8.6 m/s, which is classed on the Beaufort scale as level 3 – a gentle breeze. The prevailing wind direction was east.

At the end of week 1, frame 1 was brought inside for analysis; frames 2 and 3 remained outside. As there were no obvious alterations in the severance morphologies, the weapon type could still be identified. The cut measurements can be seen in table 14.

	Double edged blade (max width 24mm)		**Single edged blade (max width 19.5mm)**	
Cut lengths (mm)	**Warp**	**Bias**	**Warp**	**Bias**
Before weathering (mm)	24, 25, 25, 25, 30	13, 13, 16, 16, 17	21, 24, 27, 28, 29.5	21, 21, 21, 21, 22
After weathering (mm)	24, 25, 25, 25, 30	13, **13.5**, 16, 16, 17	21, 24, 27, 28, 29.5	21, 21**, 22, 22**, 22
P value	-	0.37	-	0.18

Table 14: Frame 1 cut lengths (mm) before and after weathering with P values after t-test analysis. Altered cuts are in bold.

The stab cuts in the warp direction remained unaltered for both knives; therefore t-test analysis was not necessary. T-test analysis revealed that there is no statistical difference between the stab cuts created before and after outdoor exposure in the bias with the double edged blade (P=0.37) or with the single edged blade (P=0.18). From the 20 stab cuts created for frame 1, only 3 (15%) increased in length during this 1 week period of outdoor exposure.

4.3.2 After 4 weeks: frame 2

Throughout the next 3 weeks (weeks 2-4), the samples were exposed to temperatures no warmer than in week 1 (10.3^{0}C), but the lowest temperature dropped to -3.3^{0}C during week 2. The maximum weekly average of rainfall was in week 2 (1.14mm), and the most that fell in any 12 hour period was also during that week (6.6mm). Heavy snow was not included in precipitation readings. The wind varied throughout the 3 weeks, displaying both level 3 (gentle breeze) and 4 (moderate breeze) on the Beaufort scale with the most prevailing winds being equally east and southwest.

At the end of week 4, frame 2 was brought inside for analysis after the snow was removed from each strip. There were no obvious alterations in the severance morphologies and so the weapon type could still be identified. The cut measurements can be seen in table 15.

	Double edged blade (max width 24mm)		**Single edged blade (max width 19.5mm)**	
Cut lengths (mm)	**Warp**	**Bias**	**Warp**	**Bias**
Before weathering (mm)	17, 23.5, 25, 26, 26	8, 13, 16, 16, 25	19, 20, 22, 26.5, 32	8, 14.5, 21.5, 22.5, 25
After weathering (mm)	17, **24,** 25, **26.5, 28**	**8.5,**13, **17.5, 18**, 25	19**, 21, 24, 27, 32.5**	8**, 15.5, 23, 23.5, 27**
P value	0.18	0.12	0.08	0.03*

*Table 15: Frame 2 cut lengths (mm) before and after weathering and P values after t-test analysis. Where P<0.5, this indicates a significant different and is marked *. Altered cuts are in bold.*

T-test analysis revealed that there is no statistical difference in the stab cuts before and after outdoor exposure when created with the double edged blade in the warp (P=0.18) or in bias (P=0.12). Similarly, there is no statistical difference in the stab cuts before and after outdoor exposure when created with the single edged blade in the warp (P=0.08). However, T-test analysis did reveal that there *is* a statistical difference in the stab cuts before and after outdoor exposure when created in the bias with the single edged blade (P=<0.05). Overall, from the 20 cuts on frame 2, 14 (70%) increased in length after 4 weeks of outdoor exposure.

4.3.3 After 8 weeks: frame 3

Throughout the remaining 4 weeks, the temperature range increased as it rose to 16.2^{0}C on more than one occasion, and the lowest temperature dropped to -4.0^{0}C during week 5. The maximum weekly average of rainfall never rose above that in week 2 (1.14mm), and the most that fell in any 12 hour period was also that week at 6.6mm. The wind varied throughout the 4 weeks, displaying both level 3 (gentle breeze) and 4 (moderate breeze) on the Beaufort scale with the most prevailing winds being equally east and southwest.

At the end of 8 weeks, frame 3 was brought inside for analysis. Each fabric strip was increasingly dirty towards the bottom of the frame. There were no obvious alterations in the severance morphologies of most cuts and so the weapon type could still be identified. The cut measurements can be seen in table 16.

	Double edged blade (max width 24mm)		**Single edged blade (max width 19.5mm)**	
Cut lengths (mm)	**Warp**	**Bias**	**Warp**	**Bias**
Before weathering (mm)	17, 26, 28, 29, 29	15, 16, 18, 19, 19.5	20, 21.5, 22, 23, 25	19, 23, 23.5, 26, 26
After weathering (mm)	**17.5, 27.5,** 28, **29.5, 29.5**	**17, 17, 19, 20, 21.5**	20, 21.5, 22, 23, 25	**20.5, 25, 27,** 26**,** 28
P value	0.07	0.005*	-	0.03*

*Table 16: Frame 3 cut lengths (mm) before and after weathering and P values after t-test analysis. Where P<0.5, this indicates a significant different and is marked *. Altered cuts are in bold.*

T-test analysis revealed that there is no statistical difference between the stab cuts before and after outdoor exposure when created in warp with either the double edged blade (P=0.07), or the single edged blade (no change).

In contrast, there are statistical differences in the stab cuts before and after outdoor exposure when created in the bias with both the double edged blade (P<0.05) and the single edged blade (P<0.05). Overall, from the 20 cuts on frame 3, 13 (65%) increased in length after 8 weeks of outdoor exposure.

4.4 Comparisons between the weathering frames

4.4.1 The weather

The temperature range increased throughout the exposure period from 12.2^{0}C for frame 1, to 13.6^{0}C for frame 2 and 20.2^{0}C for frame 3. As the samples were being placed on the roof, violent whipping of the samples was observed – this easterly 'gentle breeze' was recorded as equivalent to level 3 on the Beaufort scale, yet was capable of such an effect. After week 1, the wind speed rose to level 4 (moderate breeze) at various times during the remaining 7 weeks and included a south westerly wind direction. There was not a significant amount of rainfall but the frequency of exposure was increased as the samples remained outside. Rainfall measurement do not account for the snow melt in week 4 which would have saturated the samples.

4.4.2 Thickness

The fabric thickness was measured before and after exposure. Any alteration of the fabric thickness may indicate dimensional alteration, fibre swell or fibre loss. These considerations were necessary as shrinkage or expansion of the cut length may have been attributed to dimensional alteration of the fabric and not just of the cut. The 3 possibilities are as follows:

i. The fabric remains unaltered through weathering. It has neither shrunk nor stretched and no fibres have swollen.

ii. The fabric is thicker. This would indicate permanent swelling of the fibres or shrinkage of the fabric.

iii. The fabric is thinner. This would indicate stretch. For this fabric, the decrease in thickness would not have been attributed to fibre loss due to the fibre type (long) and fabric construction, or through abrasion due to the samples being suspended.

All the fabric samples were place in a standard testing atmosphere 24 hours before testing and then readings were taken using a fabric thickness tester. The fabric displayed an even surface and consistent readings both before and after weathering. For every test, there was neither an increase nor decrease in fabric thickness after weathering (table 17). It is now not necessary to consider whether the stab cut length is affected by alteration of the fabric dimensions due to outdoor exposure.

	Frame 1		Frame 2		Frame 3	
	Before weathering	After weathering	Before weathering	After weathering	Before weathering	After weathering
1	0.2	0.2	0.2	0.2	0.2	0.2
2	0.2	0.2	0.2	0.2	0.2	0.2
3	0.2	0.2	0.2	0.2	0.2	0.2
4	0.2	0.2	0.2	0.2	0.2	0.2
5	0.2	0.2	0.2	0.2	0.2	0.2
Mean	**0.2 mm**	**0.2 mm**	**0.2 mm**	**0.2 mm**	**0.2 mm**	**0.2 mm**

Table 17: Fabric thickness (mm) for all 3 frames, before and after weathering.

4.4.3 Weapon identification

The visual assessments were carried out once dried and then spot checked at a later time without prior knowledge of the weapon type. It was possible to identify the 2 weapons on every stab cut in each direction on all 3 frames before and after weathering.

4.4.4 Statistical comparisons

Below is a summary of the *P* values generated through t-test analysis, which indicates any significant changes to the stab cuts lengths after outdoor exposure (table 18).

	Frame 1	(1 week)	Frame 2	(4 weeks)	Frame 3	(8weeks)
P values	Warp	Bias	warp	Bias	Warp	Bias
Double edged blade	-	0.37	0.18	0.12	0.07	0.005*
Single edged blade	-	0.18	0.08	0.03*	-	0.03*

*Table 18: Summary of t-test analyses to identify any statistical significant differences between before and after weathering. Where P<0.5, this indicates a significant different and is marked *.*

For stab cuts created in the warp direction, no significant differences were found after weathering for either knife, for any of the 3 time periods.

For stab cuts created in the bias, the stab cuts remained stable after 1 week of exposure. After 4 weeks, stab cuts from the single edged blade display significant change. After 8 weeks, both the double edged and single edged blades altered significantly. The 2 bias stab cuts that resembled slash cuts remained un-severed.

The percentage of total altered cuts rose from 15% for frame 1, to 70% for frame 2 and then decreased slightly at 65%.

The stab cut with the largest alteration through weathering by outdoor exposure was on frame 3 which had been outside for 8 weeks (figures 73 & 74). The cut was made with the single edged blade in the bias direction.

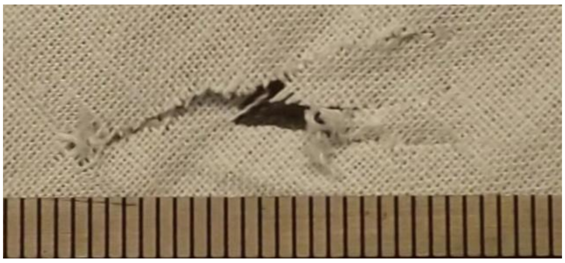


Figure 73: Before weathering – bias stab cut 23.5mm in length (single edged blade).

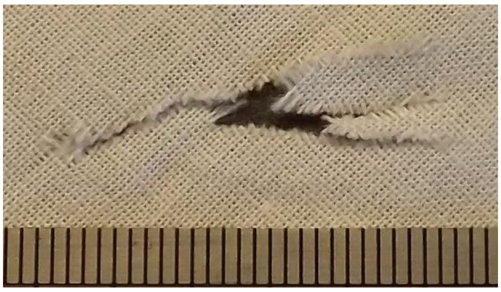


Figure 74: After weathering – bias stab cut 27mm in length (single edged blade).

The conclusions for weathering are presented in chapter 5.

Chapter 5: Conclusions

5.1 Stab force conclusion

The aim of this research was primarily to investigate whether the force required to puncture fabric differs depending on the direction of the knife in relation to the fabric weave; it was never intended to create data that purports to be a realistic interpretation of a particular scenario. These results are for comparative purposes only within this study. Valid comparisons cannot be drawn between these results and those of the authors in table 1 whose studies involved the stabbing or puncturing of fabrics over skin simulants as backings [24] [26] [27] [31] [57]. This stab force experiment is unique as no backing was used; this allowed for the performance of the weapon on fabric alone to be explored. Low coefficient of variations achieved through the tensile strength test indicated that the fabric performance was consistent; therefore any variability in stab force testing was caused by the weapons on the fabric as opposed to variation within the fabric. A range of weapons (n=6) were used to stab this plain weave for the purpose of creating baseline data on which to build.

Weapon-force profiles were created to record maximum force, the coefficient of variation and to demonstrate the action of the weapon travelling through the fabric. Box plot graphs highlighted differences in direction and speed for each weapon. It is assumed by some authors that the force required to puncture fabric would decrease as the speed increases [56] [57] due to inertial effects[22], therefore, it was interesting to discover that it was possible to achieve an overlap of data for some weapons, where the slower speed could achieve low force results similar to those at a faster speed.

Nolan [56] concluded from just 3 stab cuts (2 weft, 1 bias), that the penetration force is affected by the orientation of the knife. In this study, at the slowest speed, the minimum force for each weapon to puncture was found in the warp direction; at the faster speed, this pattern disappears. Data from only 2 permutations did not overlap: the breadknife at 100mm/min between the warp and the weft, and the single edged blade with a straight spine at 2000 mm/min between the warp and weft. All other directional data per weapon and speed overlapped to varying degrees. Due to the small sample size, it is feasible to suggest that a larger sample size would have created overlapping data, which would lead to conclude that the direction has a lesser part to play when estimating the force involved in a stab event where this fabric is involved.

Overall comparisons (figure 67) show that even with a small sample size, it is possible to achieve low enough forces with the slotted head screwdriver to overlap the data from sharp knives. Hainsworth *et al*. [52] state that tip radius, blade thickness, edge sharpness and blade geometry all affect penetrability. These rules are challenged when fabric is present as individual yarns proved strong enough to influence variation within data sets, and the range of forces became more meaningful than quoting the mean force.

Knight [56] discovered that the lowest stab force achievable with a sharp knife into cadaveric tissue was 4.9N. The lowest force achieved in this plain weave 50:50 polyester cotton was similar at 4.39N with the single edged blade with the straight spine at 2000mm/min. The effect of their combination would be an interesting discovery.

Previous studies of stab cut lengths have concluded that the cut length does not reflect the knife width due to many variables which affect it [4] The stab cuts created in the stab force experiment are an attempt at understanding the interaction of the weapon with a simple fabric held taut, and not for weapon identity with the aim of reconstructing a scenario. Though the sample size was small, the coefficient of variation was less than 3% in every permutation which indicates that the cuts were reliable. This study has found that under controlled conditions, when the fabric is held taut, the natural stretch of the fabric can accommodate some of the blade width without cutting, resulting in cut lengths shorter than the full blade width. The bias cuts are always shorter than in the warp and weft directions as the fabric has more stretch in this direction, proven by the extension tests. I would expect these results to be exaggerated if the fabric was to be over stretched.

The data from this research does not relate to all fibres and weaves, and so further investigation is required involving a range of fabrics, layers and levels of degradation through laundering. The effect of fabric tension needs to be researched as it was evident through accidental slippage of the fabric that less taut fabric required increased force to penetrate. The angle of the blade to the fabric could be investigated further; this was attempted early in this research where a ‘stab cut platform’ for the Titan[4] was devised (appendix 47). Unfortunately the accessory was unable to be manufactured due to other production commitments.

To be able to answer the forensic question of “How much force was involved in the stabbing?” it is imperative that the *range* of stab forces for a variety of weapons and a range of variables are understood further as it was discovered here that very different weapons are capable of producing similar results.

5.2 Weathering conclusion

The weathering research is unique – other published studies regarding the effects of outdoor exposure focus on the use of cadavers on the surface [70, 72] or in burials [75, 76, 78, 80, 81]. In this study, samples created from a polyester cotton blend fabric with a very simple weave, remained un-backed during outdoor exposure for up to 8 weeks through a British winter. Greater changes were expected after experiencing some of the weather that the samples endured including strong winds, rain and heavy snow.

Prior to weathering, the weapon (n=2) was identifiable for each of the randomly applied stab cuts (n=60) by the blade point entry and general morphology along the cut length, when compared with a known weapon. A variety of stab cut shapes were produced with the majority attempting to follow the line of least resistance, and differing amounts of snagging occurred - overall, no precise pattern emerged. There were no significant differences in lengths of stab cuts produced between the directions for each knife.

T-test analysis revealed that for stab cuts created in the warp direction there were no significant differences in cut lengths between before and after weathering for either knife, for any of the 3 time periods. Stab cuts in the bias were progressively affected by the weather. This research has shown that the extent of weathering of the stab cuts made in this thin polyester / cotton blend fabric was dependent on the type of knife, the direction of the stab cut, and the length of exposure. Five stab cuts per permutation were created for this research, but a more substantial number of stab cuts would have provided more robust data.

Even for those stab cuts statistically altered, outdoor weathering did not alter the severance morphology of the knife stab cuts in this fabric enough to thwart identification of the weapons. The fabric damage proved to be more robust than expected. Further research is required to allow stab cut samples to 'weather' to the point at which the evidence is no longer of value.

These results only relate to this particular fabric under these specific weathering conditions. As this research is unique, there is much scope for future work involving an array of weapons, with a range of modern fabrics consisting of a variety of fibres and weave compositions, in an assortment of weather conditions. It is possible to create more controlled conditions through the use of textile testing machinery for both the creation of the stab cuts and for the weathering exposure.

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Appendix

1 – 40: Series of test reports from the stabbing force experiment

41: Stab cut lengths from the stabbing force experiment

42: Observations before weathering – stab cuts from the double edged blade

43: Observations before weathering – stab cuts from the single edged blade

44 – 46: Full weather data for February, March and April 2013

47: Stab cut platform

Appendix 1: Test report for the breadknife in the warp direction at 100mm/min.

Test Report

Test Details

Test Name:	K1 WARP 100	Date:	16/11/2012
Standard:	CB Implement Puncture Test	Required Directions:	n/a
Specimens:	5	Jaw Scheme:	K1

Procedure Settings

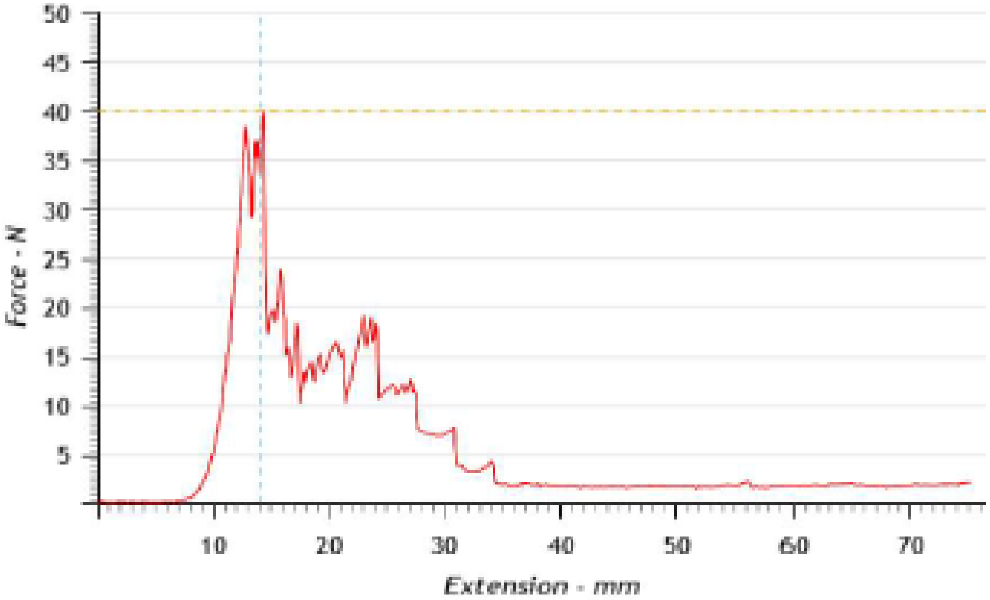
Pull To Extension

Extension:	75.00 mm
Speed:	100.00 mm/min

Results

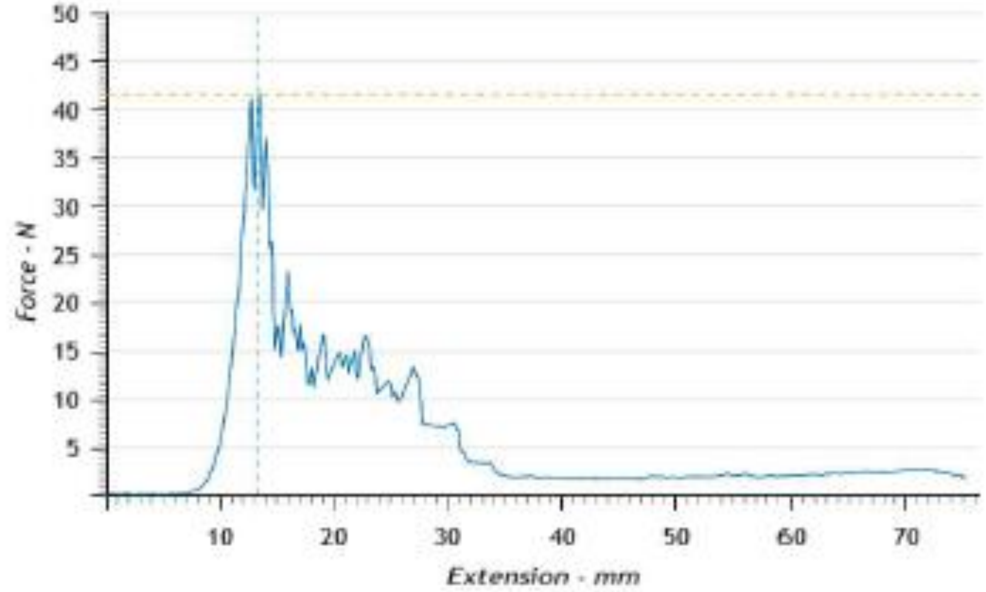
Specimen	Max Force (N)
1	39.88
2	41.46
3	41.40
4	42.57
5	40.04
Mean	41.07
Conf Limits	±1.38
Coeff Of Var	2.72%

Specimen 1 Graph

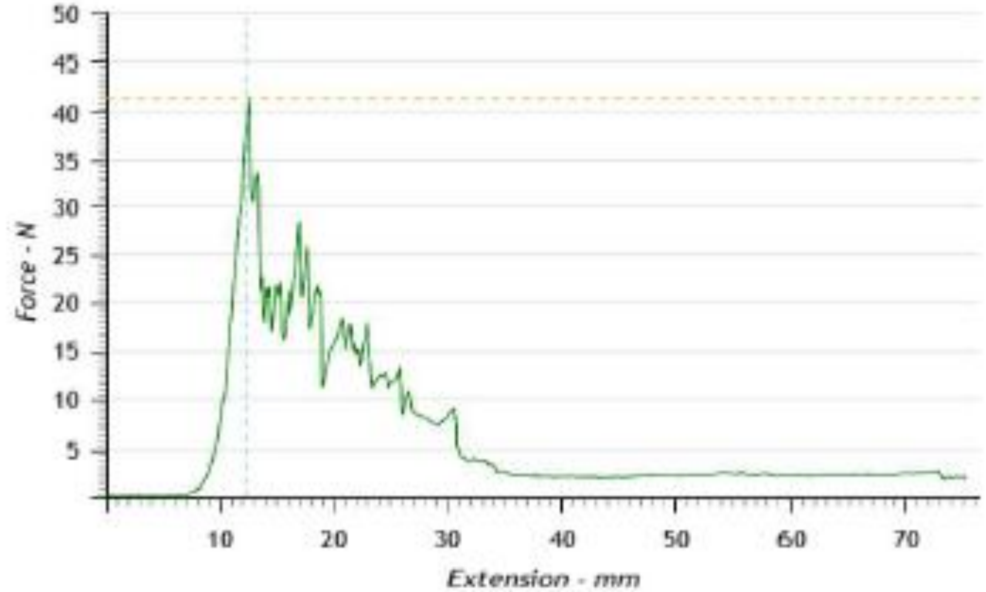


Appendix 1: Test report for the breadknife in the warp direction at 100mm/min.

Specimen 2 Graph

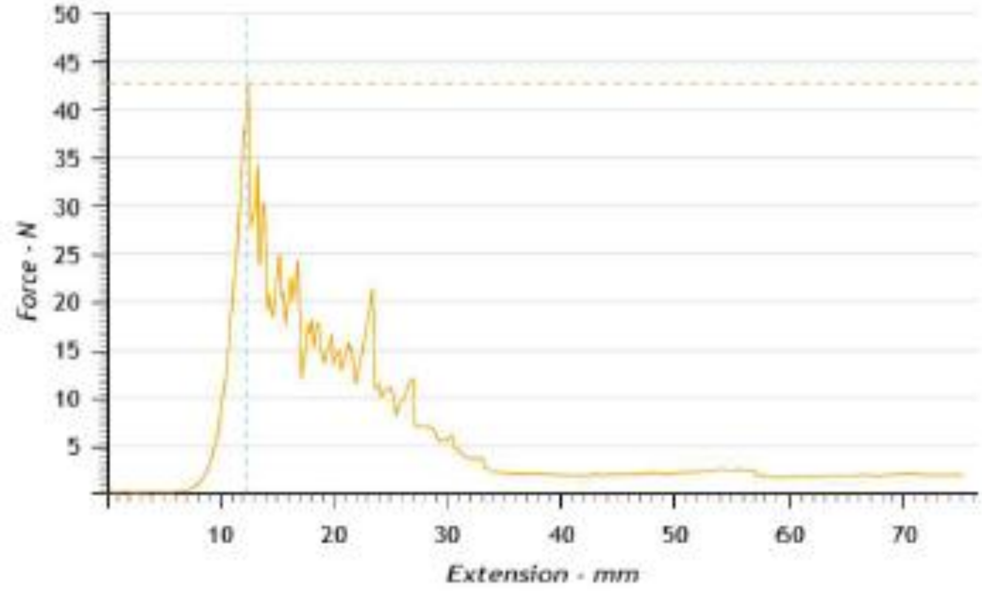


Specimen 3 Graph

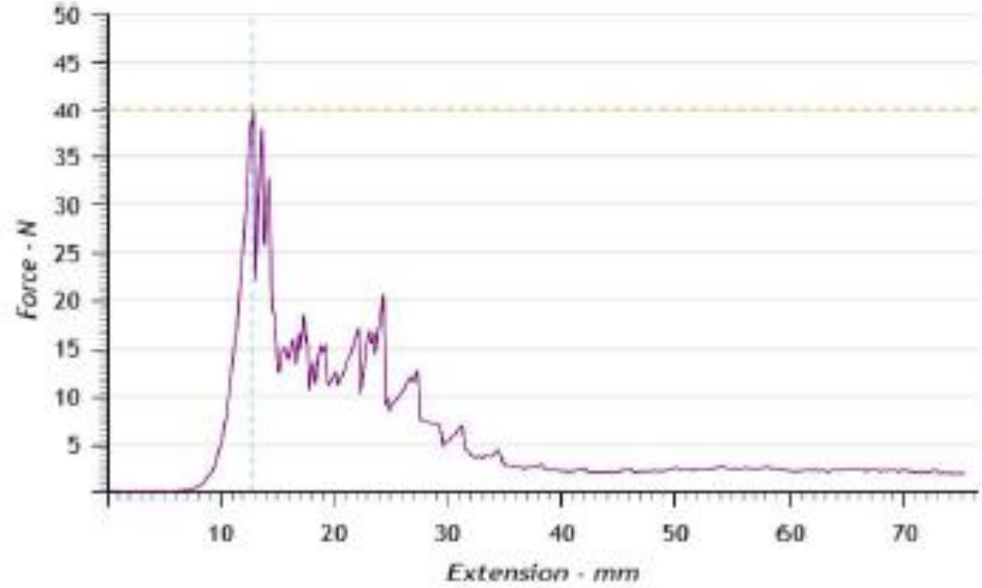


Appendix 1: Test report for the breadknife in the warp direction at 100mm/min.

Specimen 4 Graph



Specimen 5 Graph



Appendix 2: Test report for the breadknife in the warp direction at 100mm/min.

Test Report

Test Details

Test Name:	K1 WARP 2000	Date:	16/11/2012
Standard:	CB Implement Puncture Test	Jaw Scheme:	K1
Specimens:	5	Jaw Separation:	6.35 mm
Required Directions:	n/a		

Procedure Settings

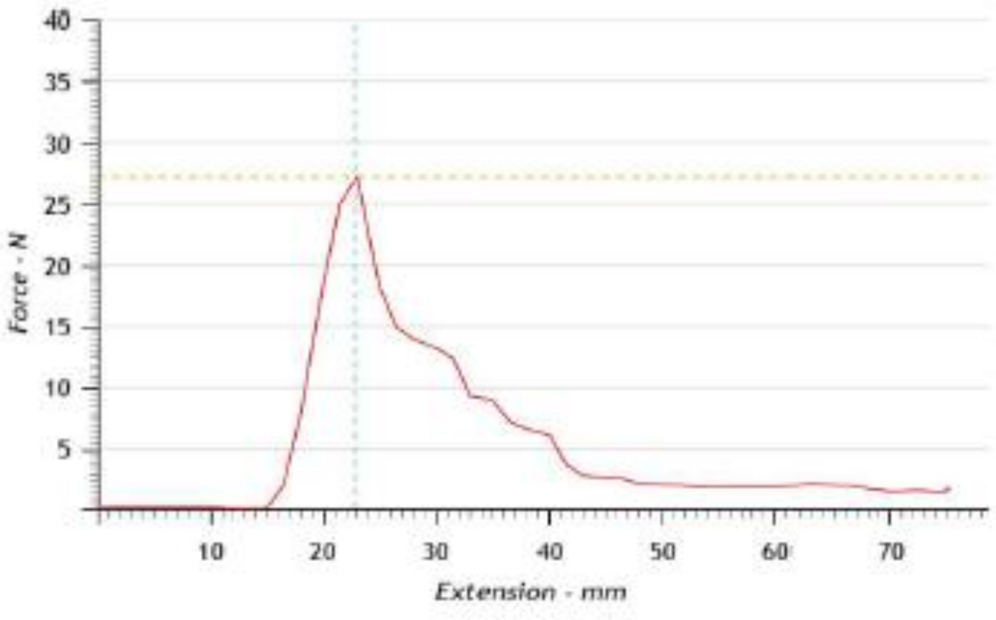
Pull To Extension

Extension:	75.00 mm
Speed:	2000.00 mm/min

Results

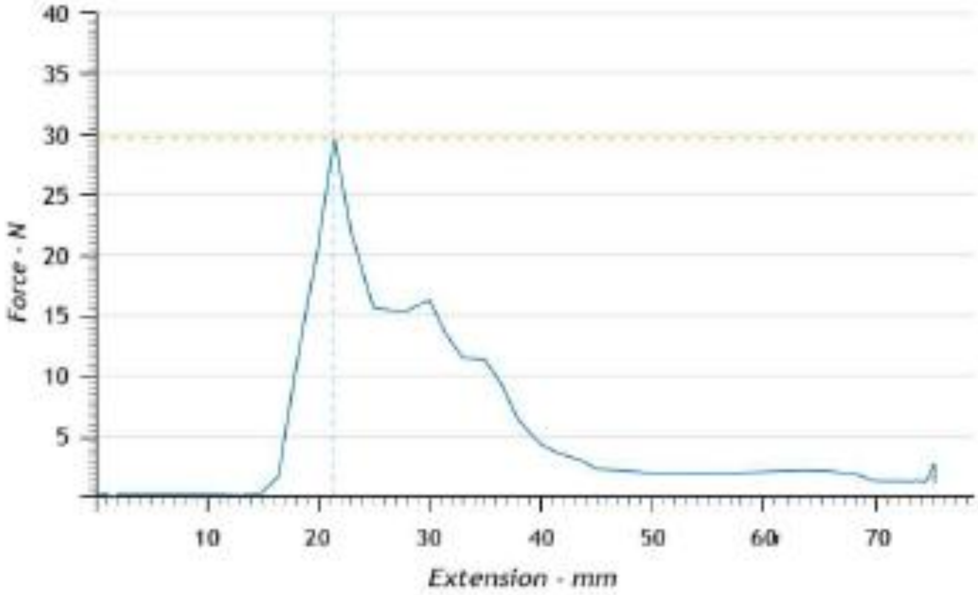
Specimen	Max Force (N)
1	27.13
2	29.55
3	25.63
4	25.88
5	33.65
Mean	28.37
Conf Limits	±4.14
Coeff Of Var	11.76%

Specimen 1 Graph

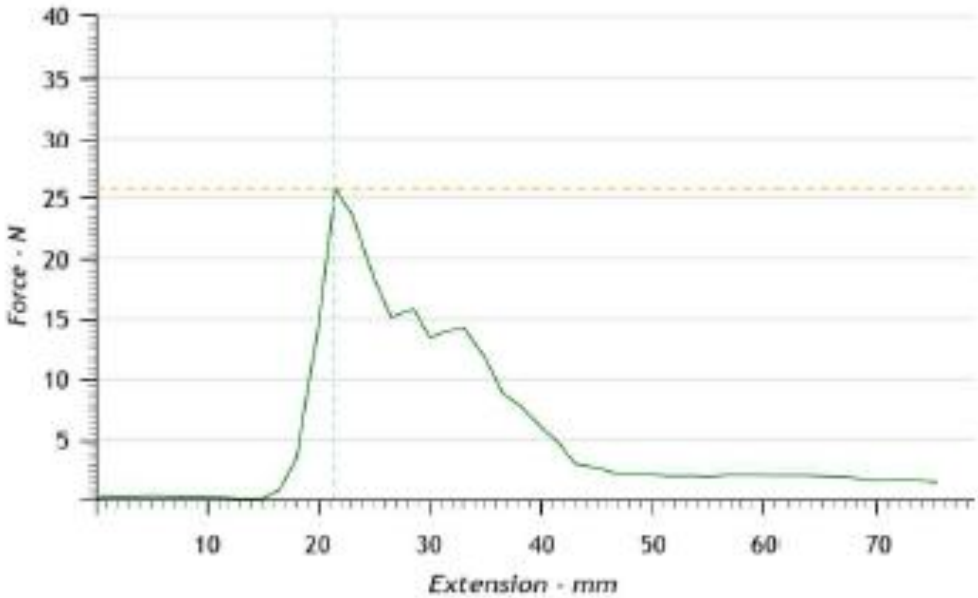


Appendix 2: Test report for the breadknife in the warp direction at 2000mm/min.

Specimen 2 Graph

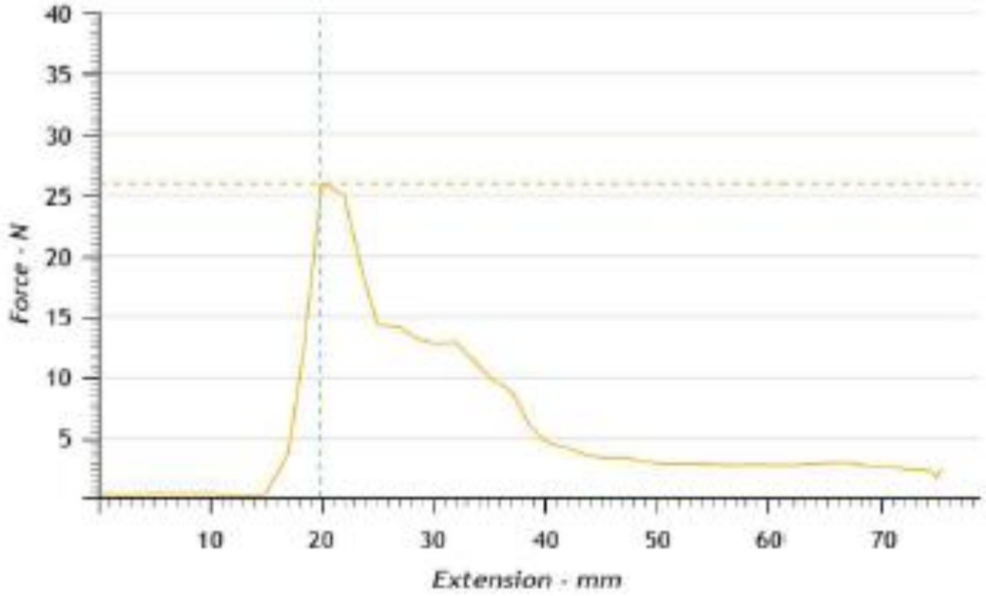


Specimen 3 Graph

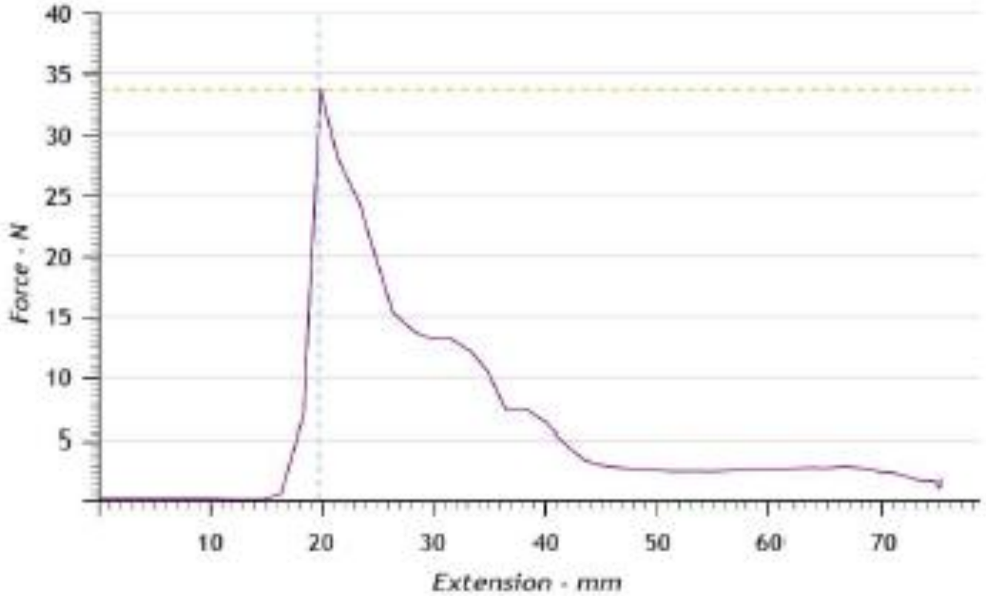


Appendix 2: Test report for the breadknife in the warp direction at 2000mm/min.

Specimen 4 Graph



Specimen 5 Graph



Appendix 3: Test report for the breadknife in the weft direction at 100mm/min.

Test Report

Test Details

Test Name:	K1 WEFT 100	Date:	16/11/2012
Standard:	CB Implement Puncture Test	Jaw Scheme:	K1
Specimens:	5	Jaw Separation:	8.14 mm
Required Directions:	n/a		

Procedure Settings

Pull To Extension

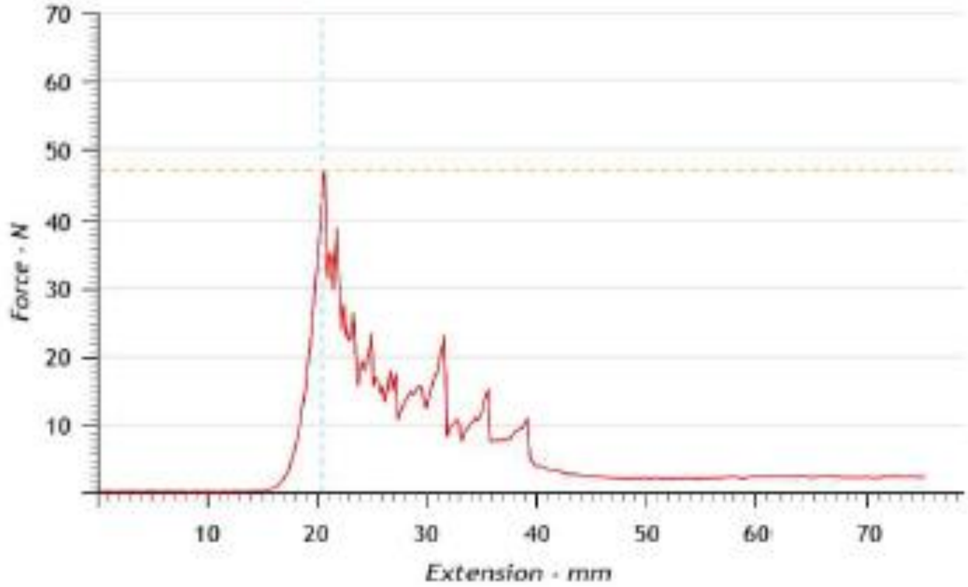
Extension:	75.00 mm
Speed:	100.00 mm/min

Results

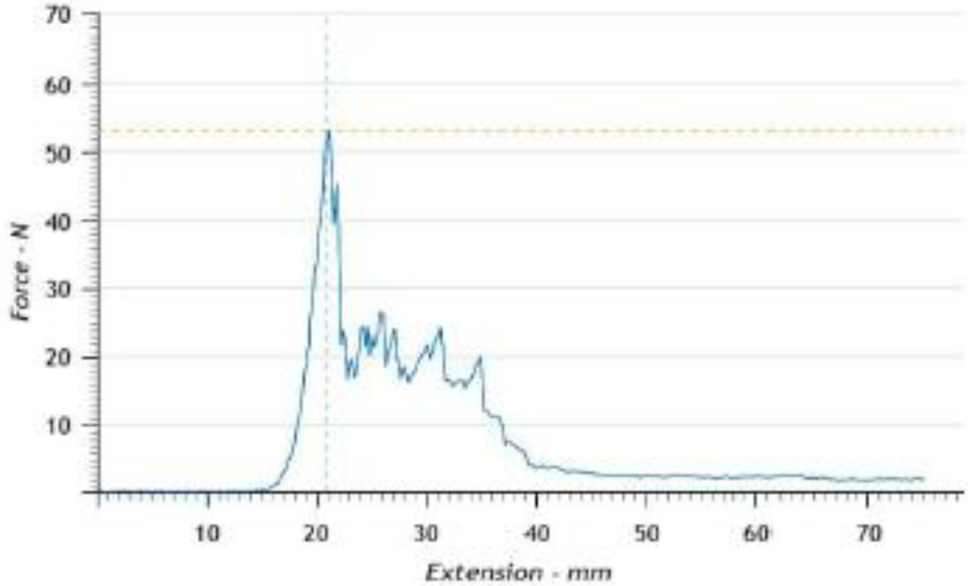
Specimen	Max Force (N)	Observation
1	46.78	
2	53.03	
3	44.28	
4	54.17	
5	64.11	SLIPPAGE IN CLAMP
Mean	52.47	
Conf Limits	±9.56	
Coeff Of Var	14.70%	

Appendix 3: Test report for the breadknife in the weft direction at 100mm/min.

Specimen 1 Graph

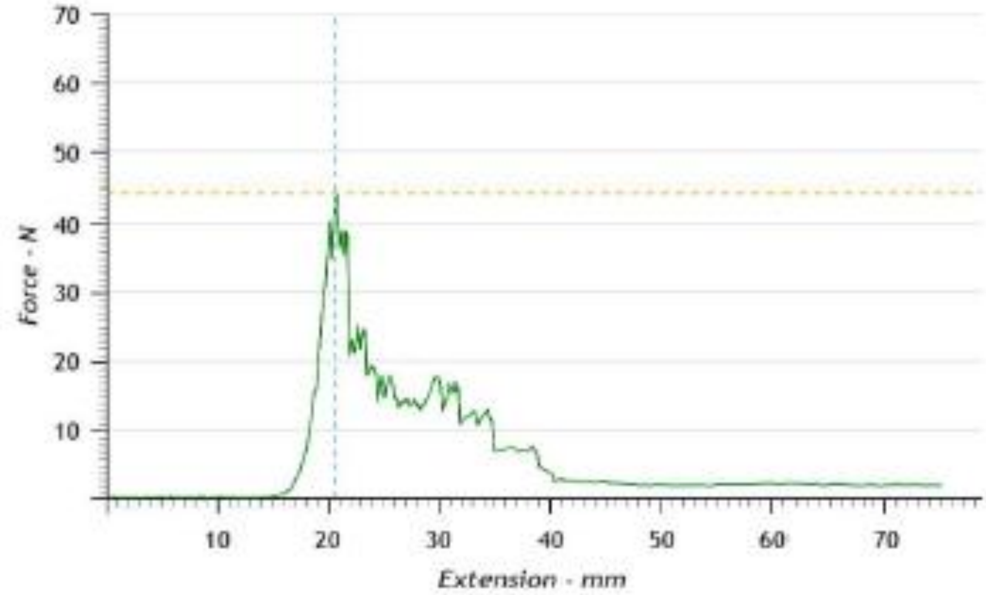


Specimen 2 Graph

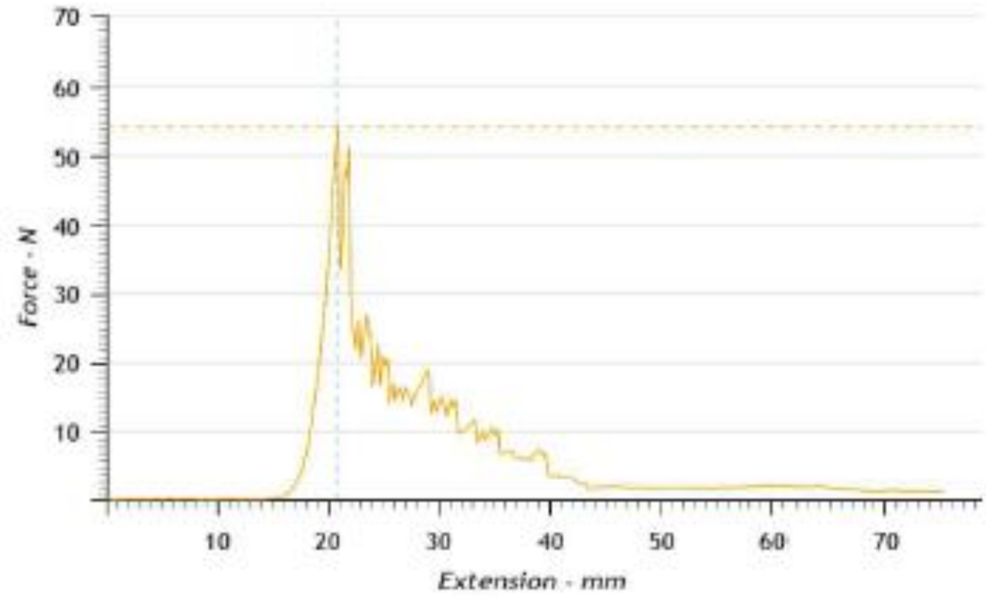


Appendix 3: Test report for the breadknife in the weft direction at 100mm/min.

Specimen 3 Graph

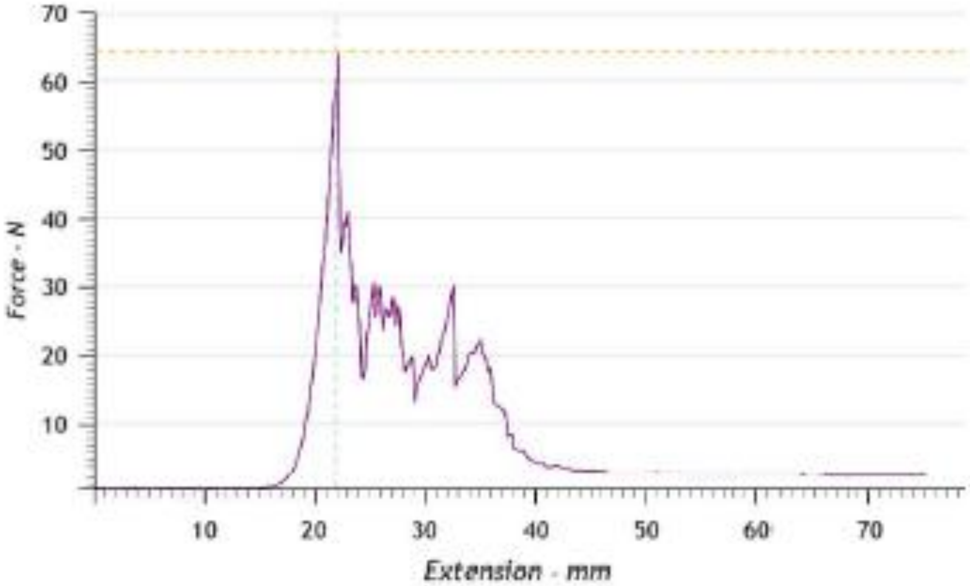


Specimen 4 Graph



Appendix 3: Test report for the breadknife in the weft direction at 100mm/min.

Specimen 5 Graph



Appendix 4: Test report for the breadknife in the weft direction at 2000mm/min.

Test Report

Test Details

Test Name:	K1 WEFT 2000	Date:	16/11/2012
Standard:	CB Implement Puncture Test	Jaw Scheme:	K1
Specimens:	5	Jaw Separation:	5.32 mm
Required Directions:	n/a		

Procedure Settings

Pull To Extension

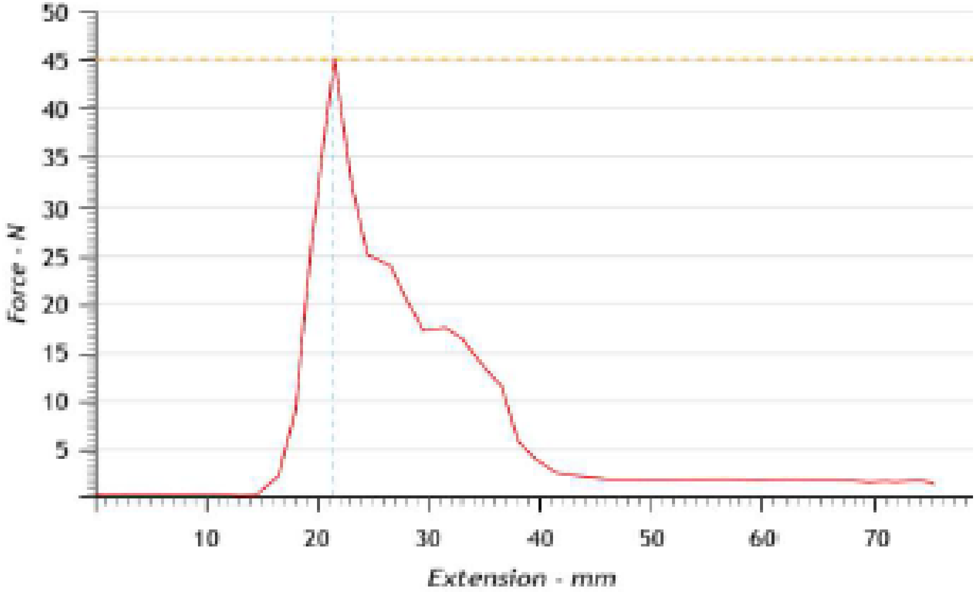
Extension:	75.00 mm
Speed:	2000.00 mm/min

Results

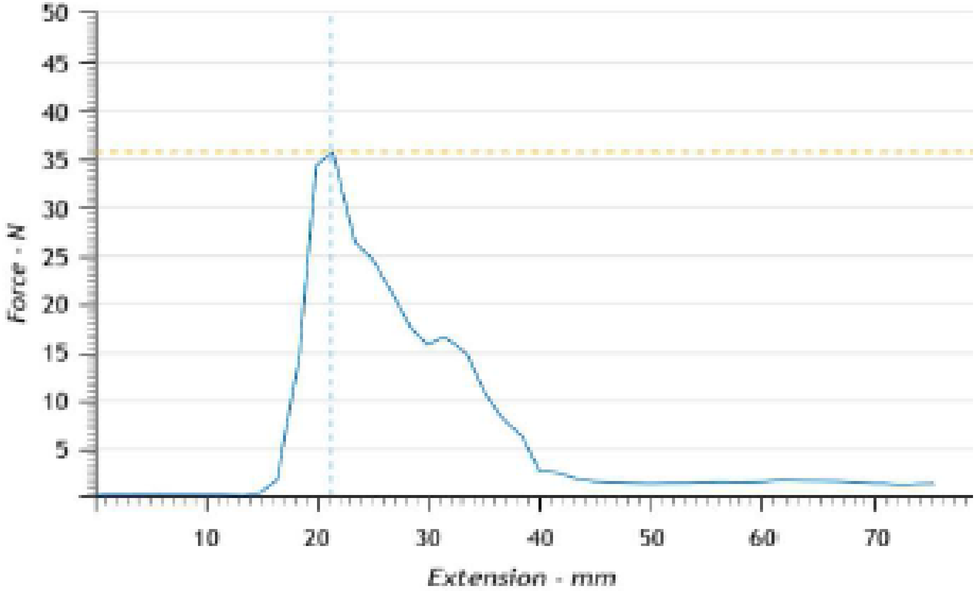
Specimen	Max Force (N)	Observation
1	45.02	SLIPPAGE IN CLAMP
2	35.63	
3	37.89	
4	35.75	
5	32.54	
Mean	37.37	
Conf Limits	±5.80	
Coeff Of Var	12.53%	

Appendix 4: Test report for the breadknife in the weft direction at 2000mm/min.

Specimen 1 Graph

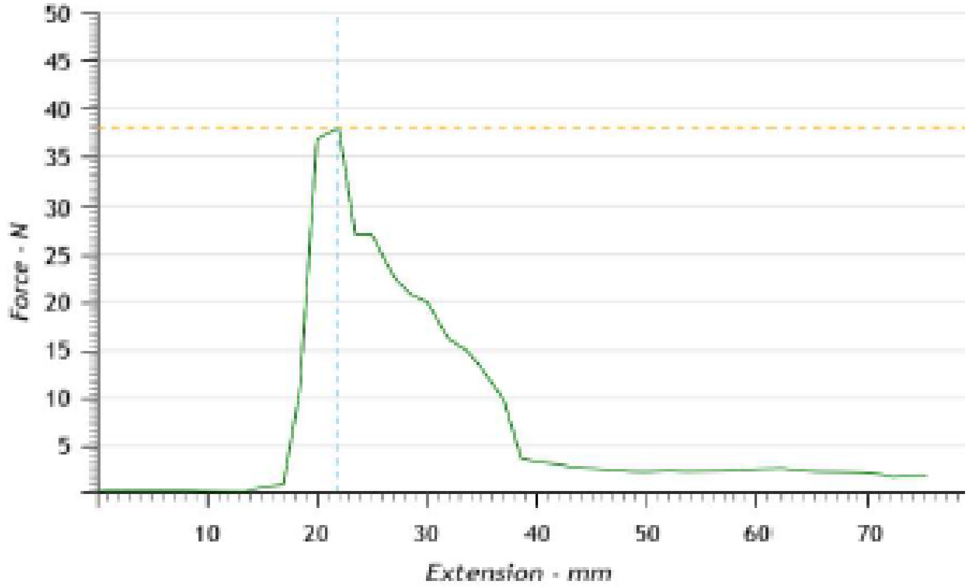


Specimen 2 Graph

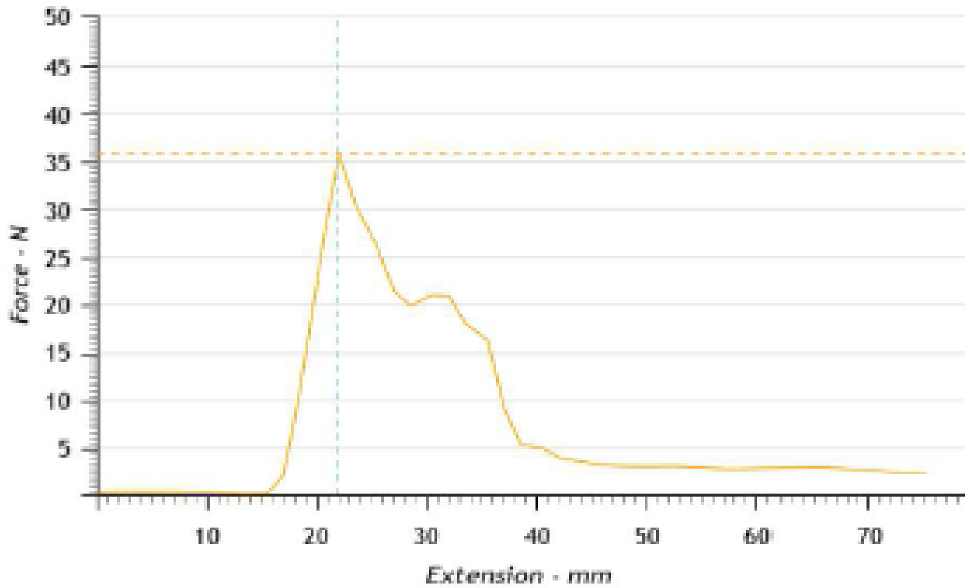


Appendix 4: Test report for the breadknife in the weft direction at 2000mm/min.

Specimen 3 Graph

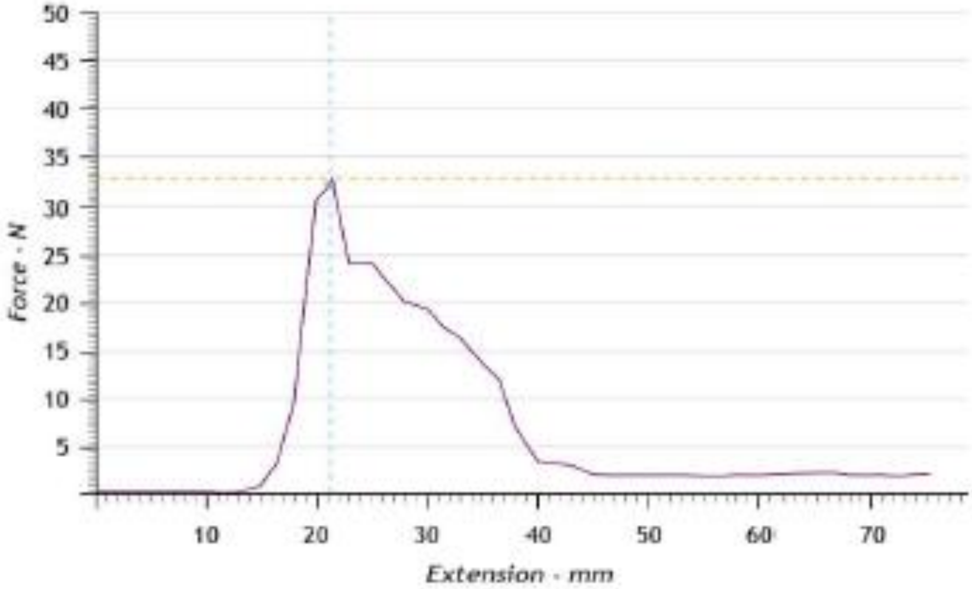


Specimen 4 Graph



Appendix 4: Test report for the breadknife in the weft direction at 2000mm/min.

Specimen 5 Graph



Appendix 5: Test report for the breadknife in the bias direction at 100mm/min.

Test Report

Test Details

Test Name:	K1 BIAS 100	Date:	16/11/2012
Standard:	CB Implement Puncture Test	Required Directions:	n/a
Specimens:	5	Jaw Scheme:	K1

Procedure Settings

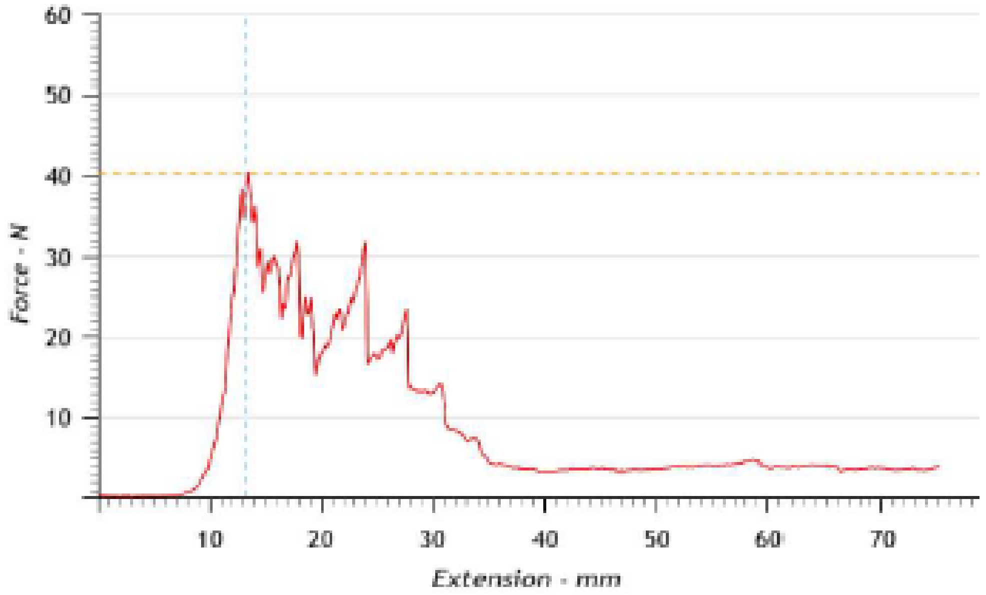
Pull To Extension

Extension:	75.00 mm
Speed:	100.00 mm/min

Results

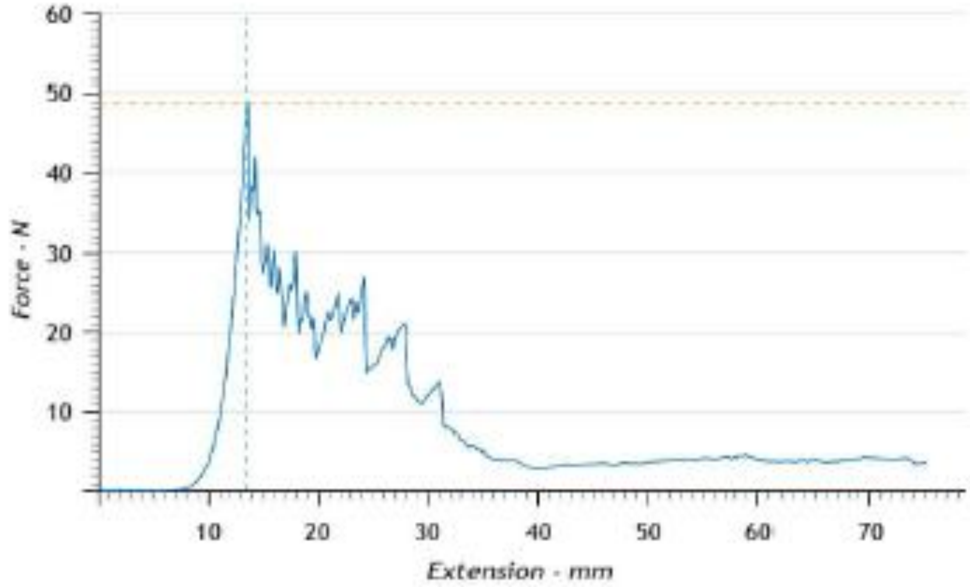
Specimen	Max Force (N)
1	40.25
2	48.68
3	41.18
4	44.98
5	51.99
Mean	45.42
Conf Limits	±6.16
Coeff Of Var	10.94%

Specimen 1 Graph

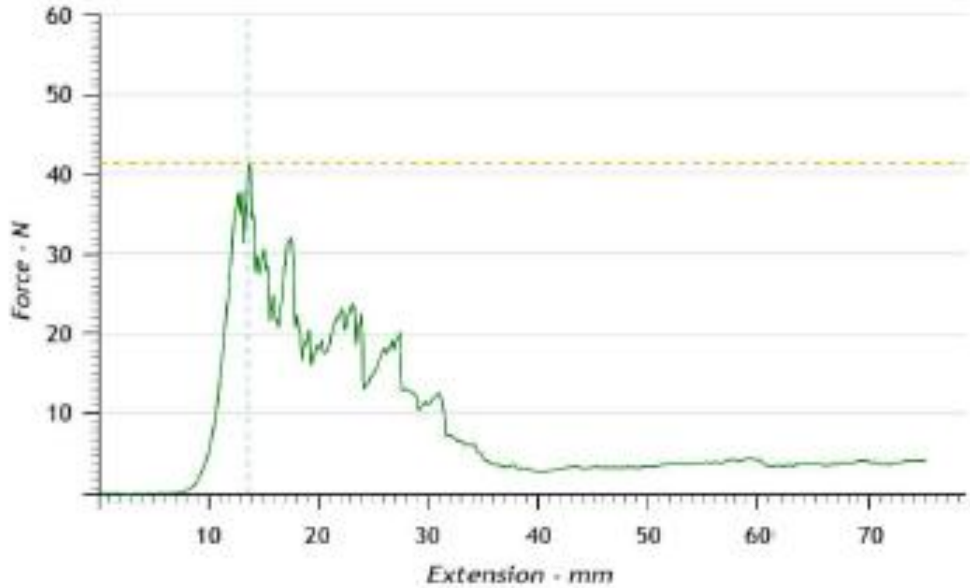


Appendix 5: Test report for the breadknife in the bias direction at 100mm/min.

Specimen 2 Graph

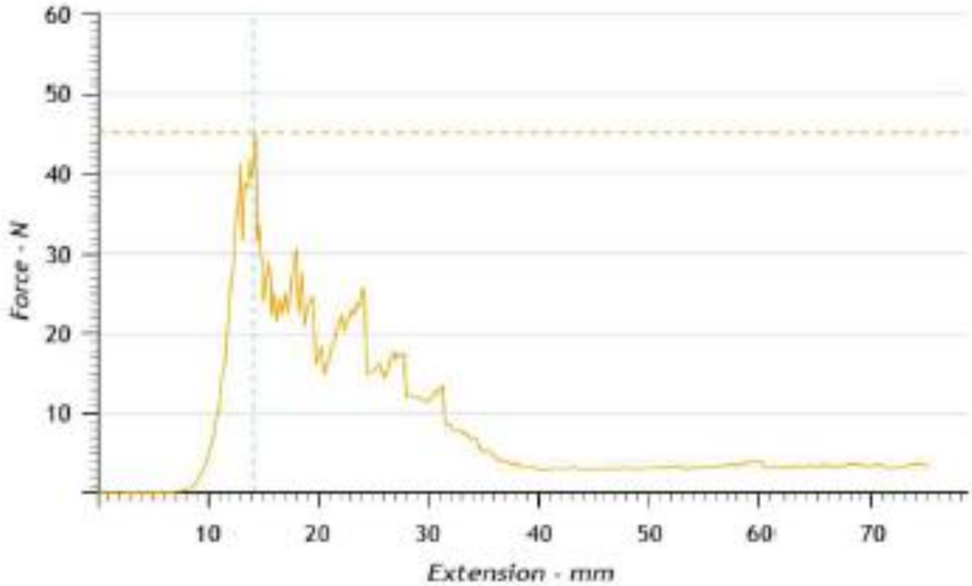


Specimen 3 Graph

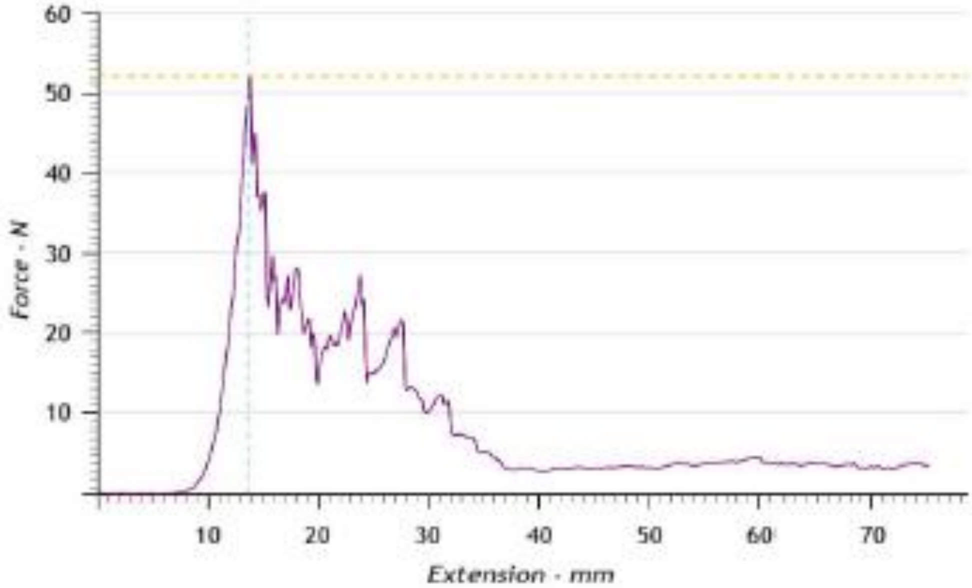


Appendix 5: Test report for the breadknife in the bias direction at 100mm/min.

Specimen 4 Graph



Specimen 5 Graph



Appendix 6: Test report for the breadknife in the bias direction at 2000mm/min.

Test Report

Test Details

Test Name:	K1 BIAS 2000	Date:	16/11/2012
Standard:	CB Implement Puncture Test	Required Directions:	n/a
Specimens:	5	Jaw Scheme:	K1

Procedure Settings

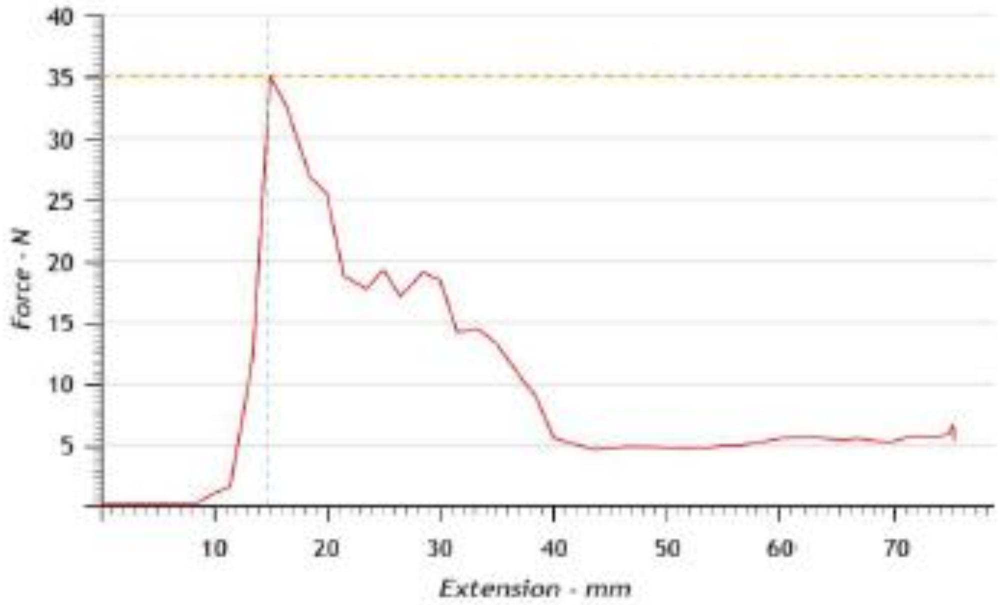
Pull To Extension

Extension:	75.00 mm
Speed:	2000.00 mm/min

Results

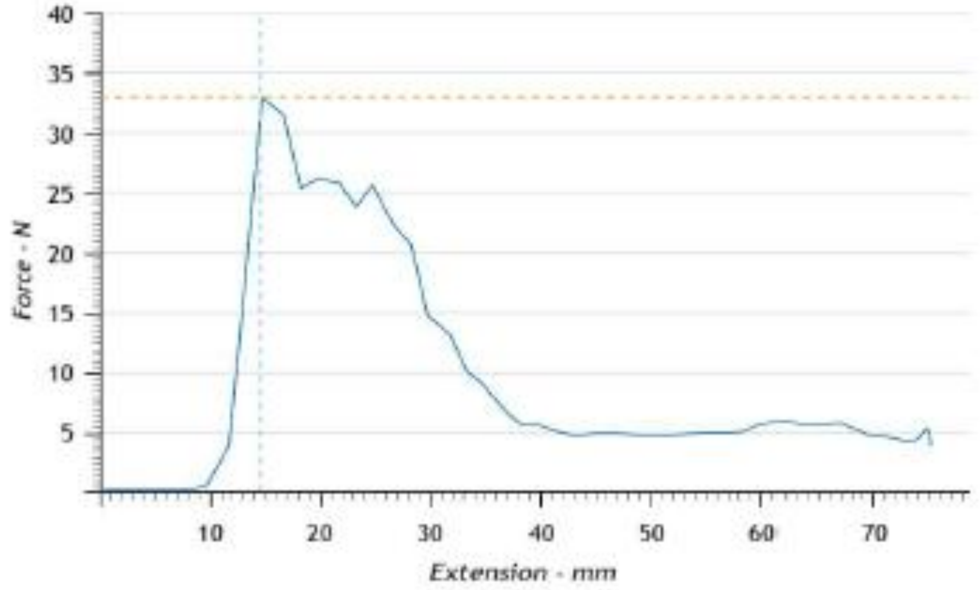
Specimen	Max Force (N)
1	35.01
2	32.92
3	33.82
4	33.52
5	31.56
Mean	33.37
Conf Limits	±1.57
Coeff Of Var	3.78%

Specimen 1 Graph

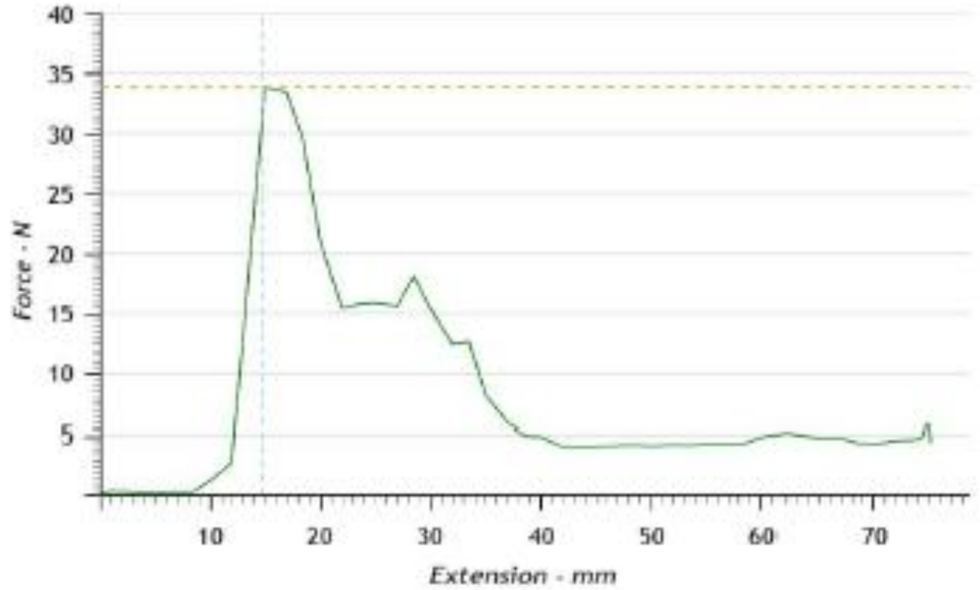


Appendix 6: Test report for the breadknife in the bias direction at 2000mm/min.

Specimen 2 Graph

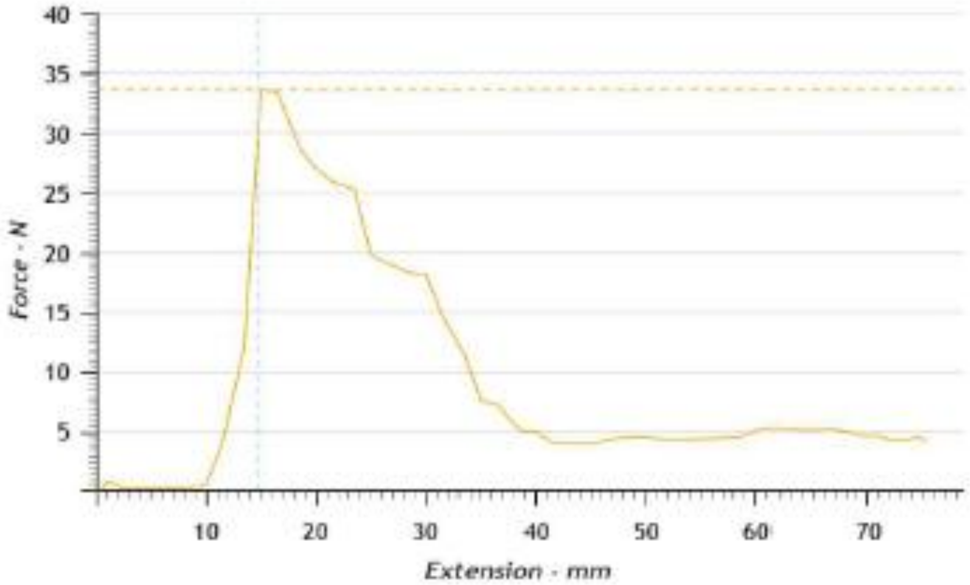


Specimen 3 Graph

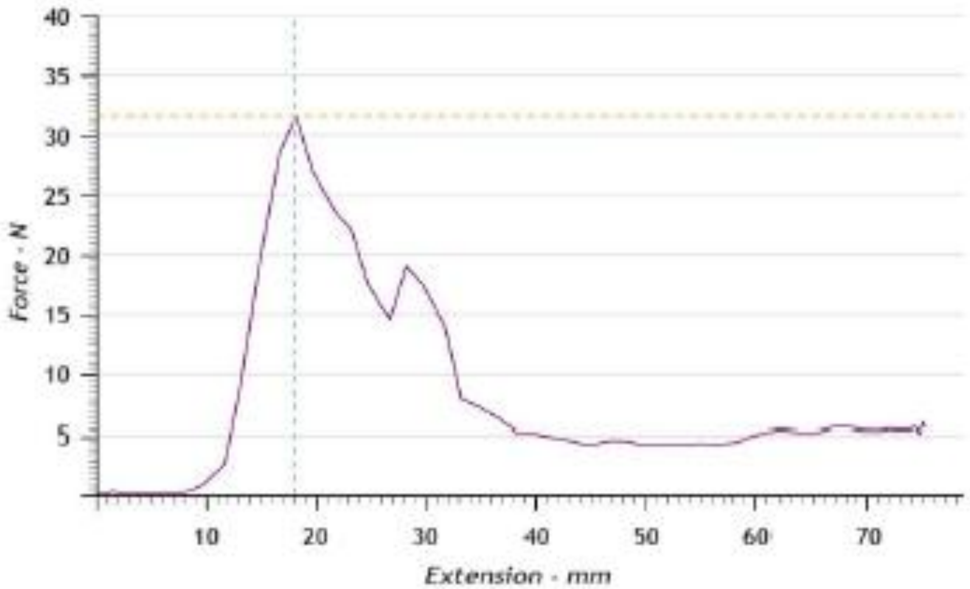


Appendix 6: Test report for the breadknife in the bias direction at 2000mm/min.

Specimen 4 Graph



Specimen 5 Graph



Appendix 7: Test report for the breadknife into paper at 100mm/min.

Test Report

Test Details

Test Name:	K1 Paper Reference	Date:	15/02/2013
Standard:	CB Implement Puncture Test	Required Directions:	n/a
Specimens:	5	Jaw Scheme:	K10

Procedure Settings

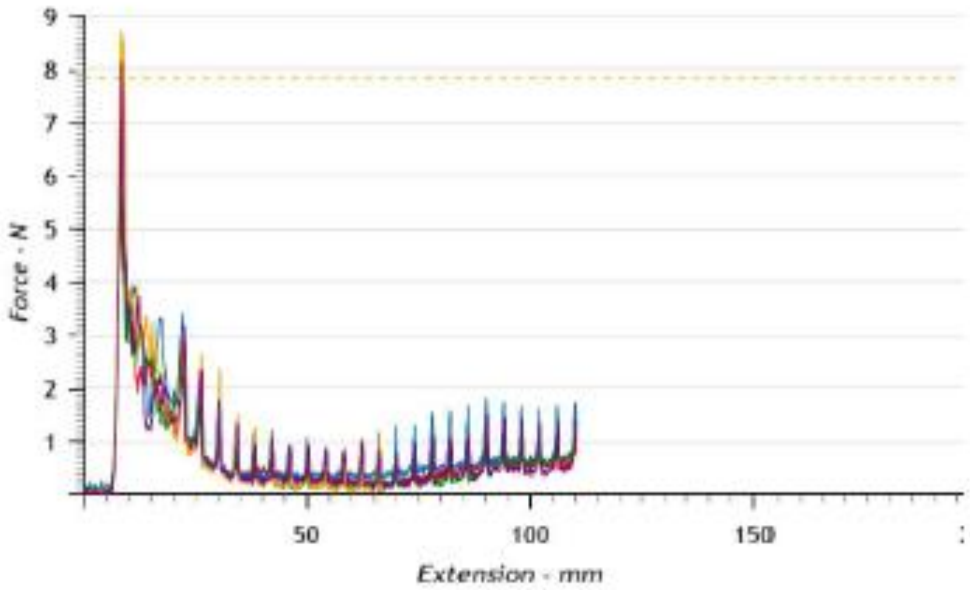
Break Detection:	100 %
Pull To Extension	
Extension:	110.00 mm
Speed:	100.00 mm/min

Results

Specimen	Max Force (N)
1	6.86
2	8.07
3	7.43
4	8.69
5	8.10
Mean	7.83
Conf Limits	±0.87
Coeff Of Var	8.95%

Appendix 7: Test report for the breadknife into paper at 100mm/min.

Graph



Appendix 8: Test report for the knife with a straight spine in the warp direction at 100mm/min.

Test Report

Test Details

Test Name:	K5 WARP 100	Date:	01/03/2013
Standard:	CB Implement Puncture Test	Required Directions:	n/a
Specimens:	5	Jaw Scheme:	K5

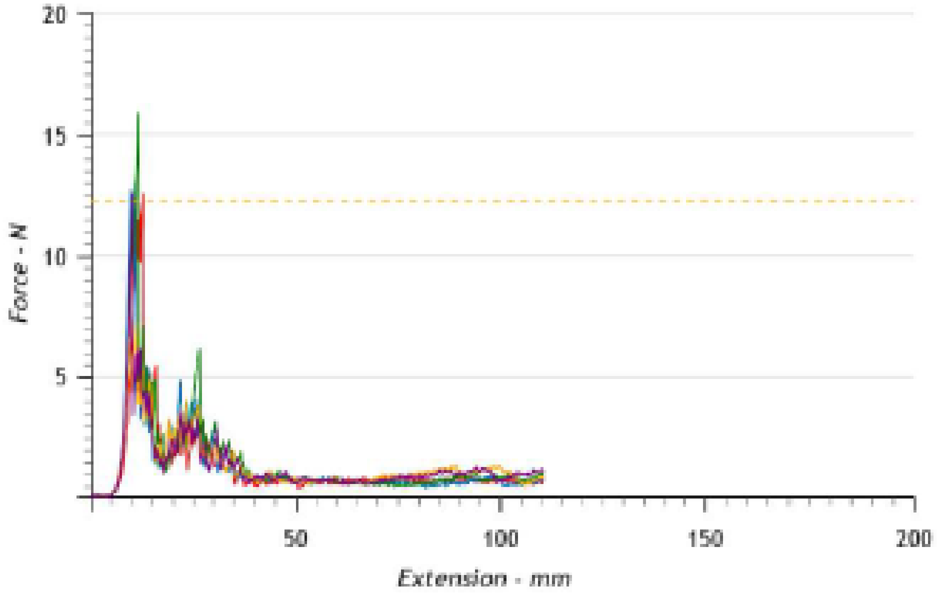
Procedure Settings

Break Detection:	100 %
Pull To Extension	
Extension:	110.00 mm
Speed:	100.00 mm/min

Results

Specimen	Max Force (N)
1	12.51
2	13.03
3	15.84
4	7.14
5	12.53
Mean	12.21
Conf Limits	±3.91
Coeff Of Var	25.82%

Graph



Appendix 9: Test report for the knife with a straight spine in the warp direction at 2000mm/min.

Test Report

Test Details

Test Name:	K5 WARP 2000	Date:	01/03/2013
Standard:	CB Implement Puncture Test	Required Directions:	n/a
Specimens:	5	Jaw Scheme:	K5

Procedure Settings

Break Detection: 100 %

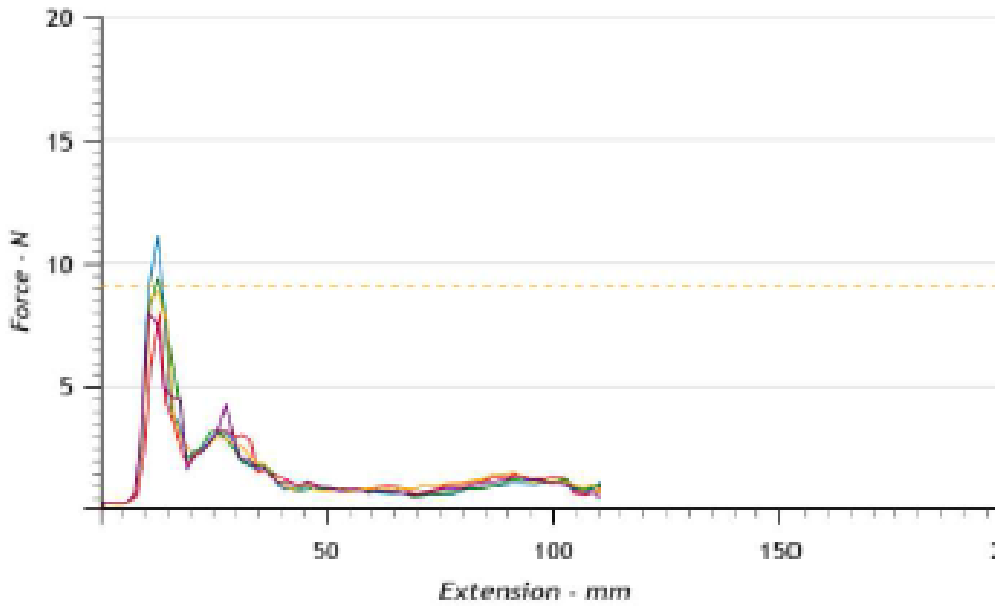
Pull To Extension

Extension: 110.00 mm
Speed: 2000.00 mm/min

Results

Specimen	Max Force (N)
1	7.96
2	11.03
3	9.35
4	8.80
5	7.96
Mean	9.02
Conf Limits	±1.57
Coeff Of Var	14.08%

Graph



Appendix 10: Test report for the knife with a straight spine in the weft direction at 100mm/min.

Test Report

Test Details

Test Name:	K5 WEFT 100	Date:	01/03/2013
Standard:	CB Implement Puncture Test	Required Directions:	n/a
Specimens:	5	Jaw Scheme:	K5

Procedure Settings

Break Detection: 100 %

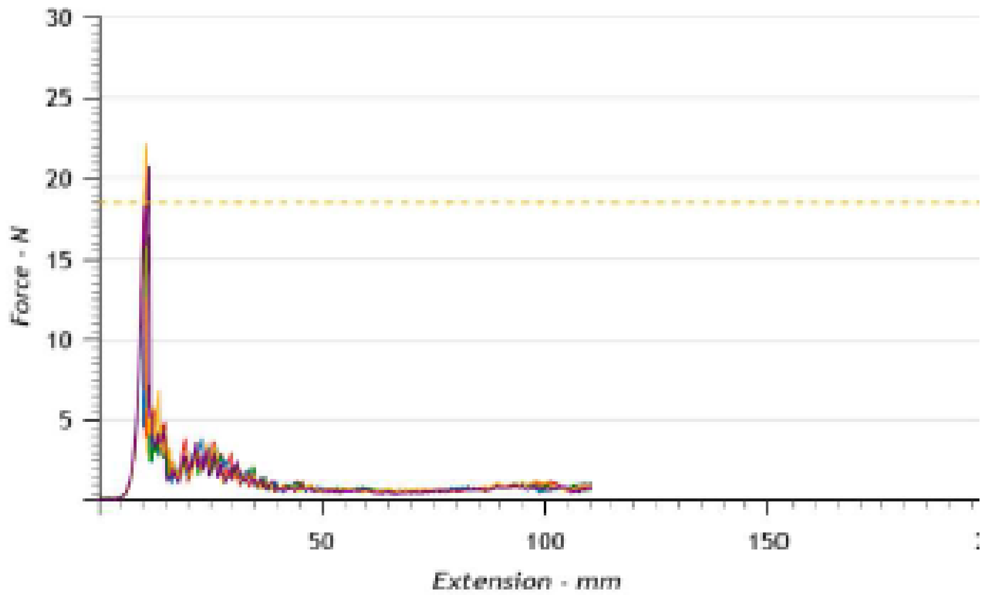
Pull To Extension

Extension: 110.00 mm
Speed: 100.00 mm/min

Results

Specimen	Max Force (N)
1	18.13
2	13.02
3	18.31
4	22.06
5	20.63
Mean	18.43
Conf Limits	±4.27
Coeff Of Var	18.67%

Graph



Appendix 11: Test report for the knife with a straight spine in the weft direction at 2000mm/min.

Test Report

Test Details

Test Name:	K5 WEFT 2000	Date:	01/03/2013
Standard:	CB Implement Puncture Test	Required Directions:	n/a
Specimens:	5	Jaw Scheme:	K5

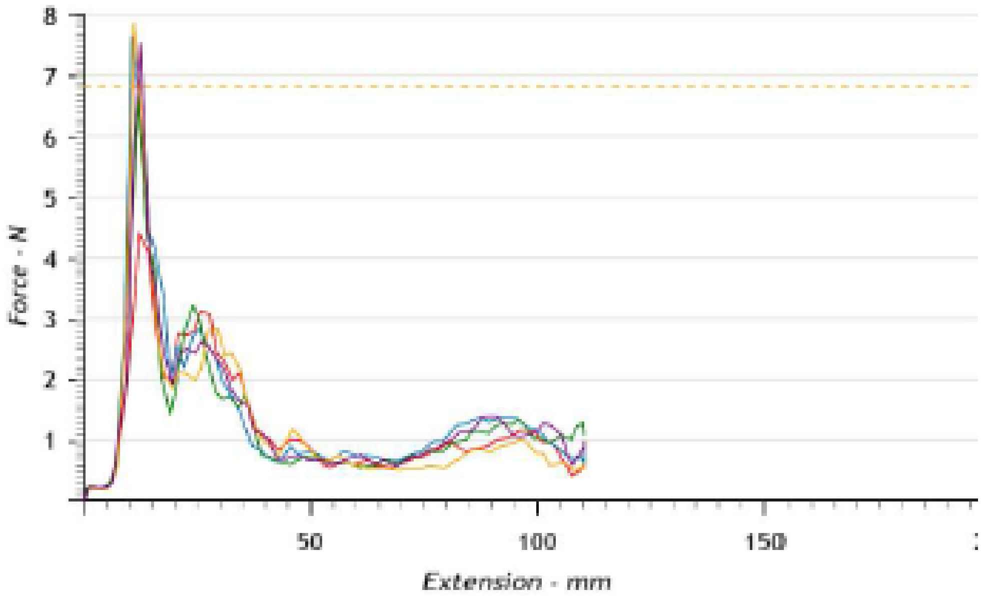
Procedure Settings

Break Detection:	100 %
Pull To Extension	
Extension:	110.00 mm
Speed:	2000.00 mm/min

Results

Specimen	Max Force (N)
1	4.39
2	7.64
3	6.64
4	7.84
5	7.51
Mean	6.80
Conf Limits	±1.77
Coeff Of Var	20.93%

Graph



Appendix 12: Test report for the knife with a straight spine in the bias direction at 100mm/min.

Test Report

Test Details

Test Name:	K5 BIAS 100	Date:	01/03/2013
Standard:	CB Implement Puncture Test	Required Directions:	n/a
Specimens:	5	Jaw Scheme:	K5

Procedure Settings

Break Detection: 100 %

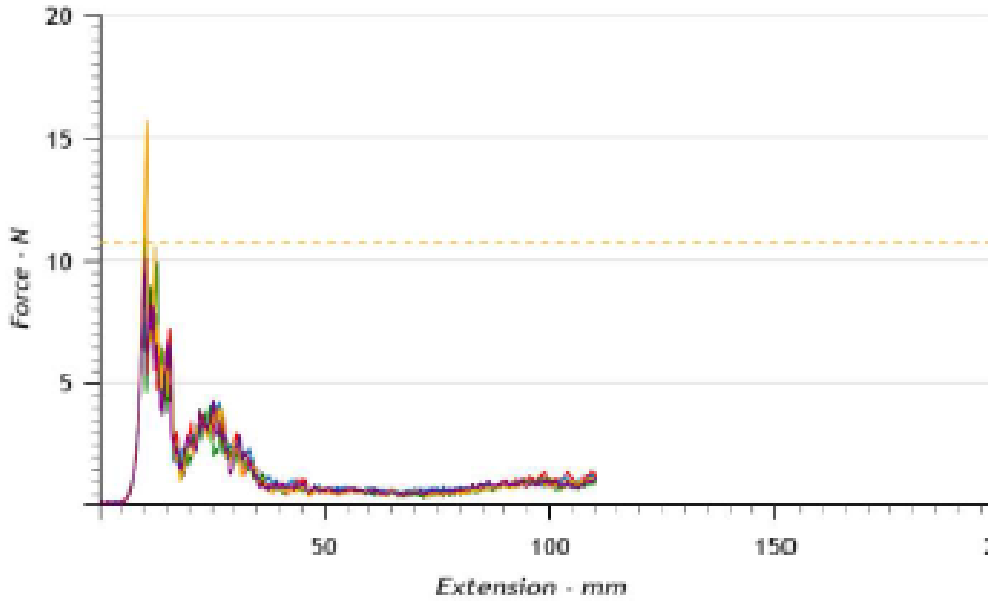
Pull To Extension

Extension: 110.00 mm
Speed: 100.00 mm/min

Results

Specimen	Max Force (N)
1	8.70
2	8.16
3	10.87
4	15.64
5	10.01
Mean	10.67
Conf Limits	±3.69
Coeff Of Var	27.85%

Graph



Appendix 13: Test report for the knife with a straight spine in the bias direction at 2000mm/min.

Test Report

Test Details

Test Name:	K5 BIAS 2000	Date:	01/03/2013
Standard:	CB Implement Puncture Test	Required Directions:	n/a
Specimens:	5	Jaw Scheme:	K5

Procedure Settings

Break Detection: 100 %

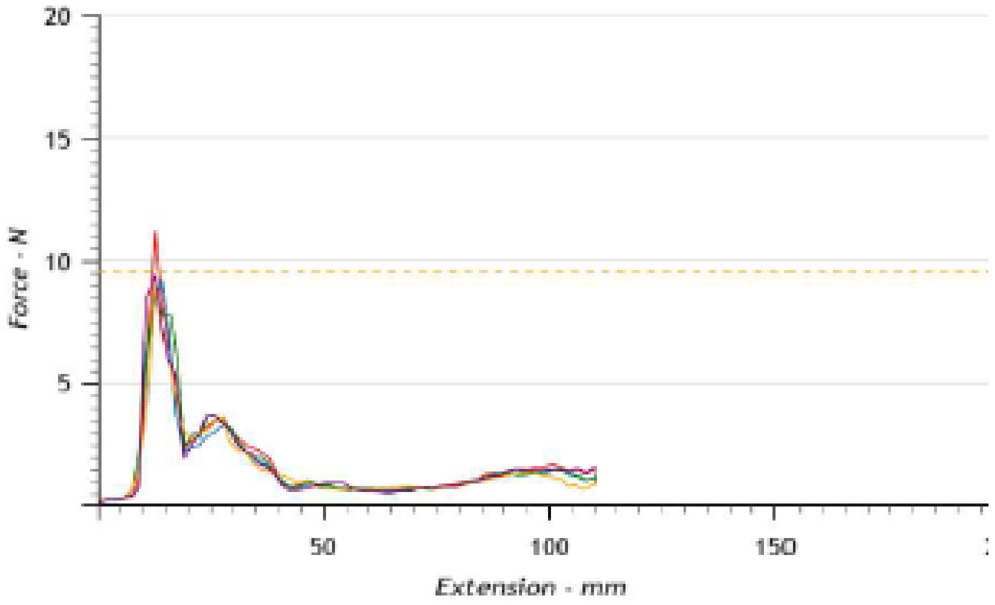
Pull To Extension

Extension: 110.00 mm
Speed: 2000.00 mm/min

Results

Specimen	Max Force (N)
1	11.13
2	9.13
3	8.86
4	9.05
5	9.35
Mean	9.50
Conf Limits	±1.15
Coeff Of Var	9.78%

Graph



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Appendix 14: Test report for the knife with a straight spine into paper at 100mm/min.

Test Report

Test Details

Test Name:	K5 PAPER 100	Date:	26/04/2013
Standard:	CB Implement Puncture Test	Jaw Scheme:	K5
Specimens:	5	Jaw Separation:	100.57 mm
Required Directions:	n/a		

Procedure Settings

Break Detection: 100 %

Pull To Extension

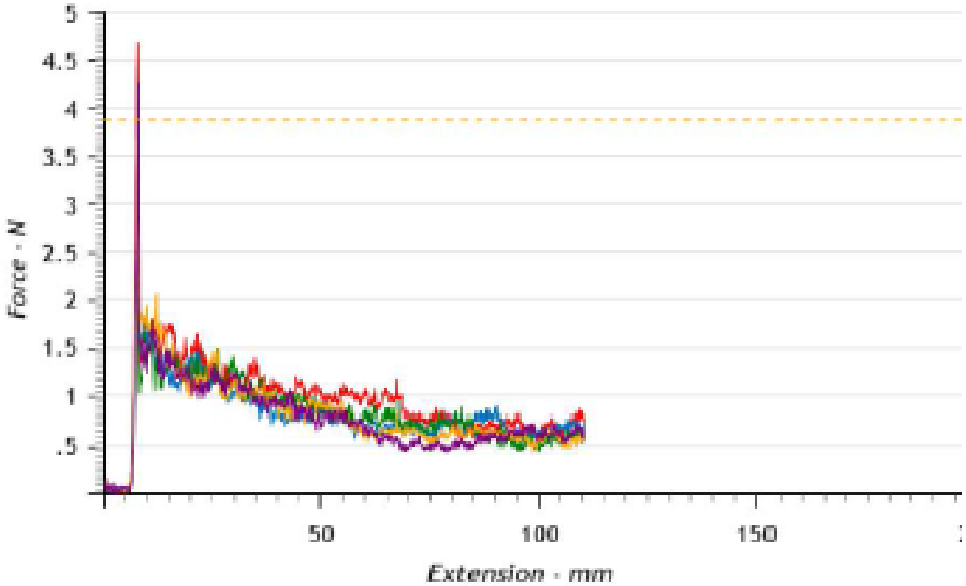
Extension: 110.00 mm
Speed: 100.00 mm/min

Results

Specimen	Max Force (N)
1	4.67
2	3.48
3	3.30
4	3.65
5	4.26
Mean	3.87
Conf Limits	±0.71
Coeff Of Var	14.81%

Appendix 14: Test report for the knife with a straight spine into paper at 100mm/min.

Graph



Appendix 15: Test report for the knife with a curved spine in the warp direction at 100mm/min.

Test Report

Test Details

Test Name:	K18 WARP 100	Date:	01/03/2013
Standard:	CB Implement Puncture Test	Required Directions:	n/a
Specimens:	5	Jaw Scheme:	K18

Procedure Settings

Break Detection: 100 %

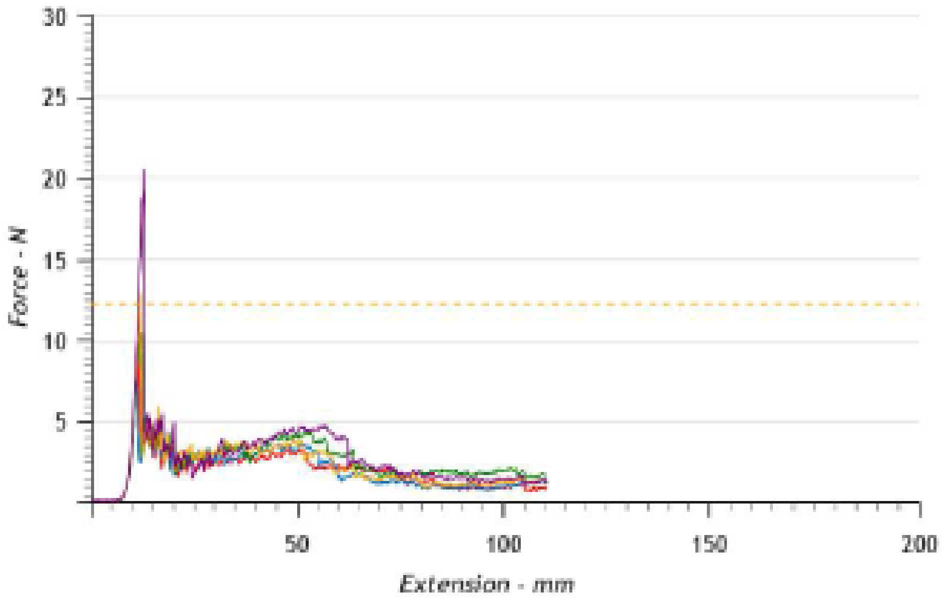
Pull To Extension

Extension: 110.00 mm
Speed: 100.00 mm/min

Results

Specimen	Max Force (N)
1	9.45
2	7.91
3	10.38
4	12.80
5	20.47
Mean	12.20
Conf Limits	±6.14
Coeff Of Var	40.55%

Graph



Appendix 16: Test report for the knife with a curved spine in the warp direction at 2000mm/min.

Test Report

Test Details

Test Name:	K18 WARP 2000	Date:	01/03/2013
Standard:	CB Implement Puncture Test	Required Directions:	n/a
Specimens:	5	Jaw Scheme:	K18

Procedure Settings

Break Detection: 100 %

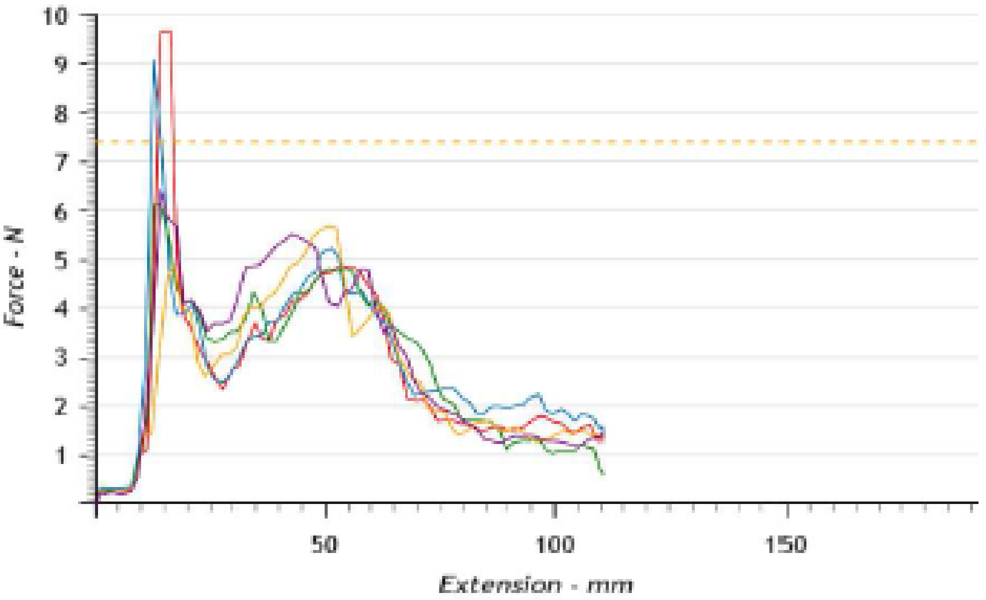
Pull To Extension

Extension: 110.00 mm
Speed: 2000.00 mm/min

Results

Specimen	Max Force (N)
1	9.65
2	9.06
3	6.12
4	5.65
5	6.40
Mean	7.38
Conf Limits	±2.28
Coeff Of Var	24.94%

Graph



Appendix 17: Test report for the knife with a curved spine in the weft direction at 100mm/min.

Test Report

Test Details

Test Name:	K18 WEFT 100	Date:	01/03/2013
Standard:	CB Implement Puncture Test	Required Directions:	n/a
Specimens:	5	Jaw Scheme:	K18

Procedure Settings

Break Detection: 100 %

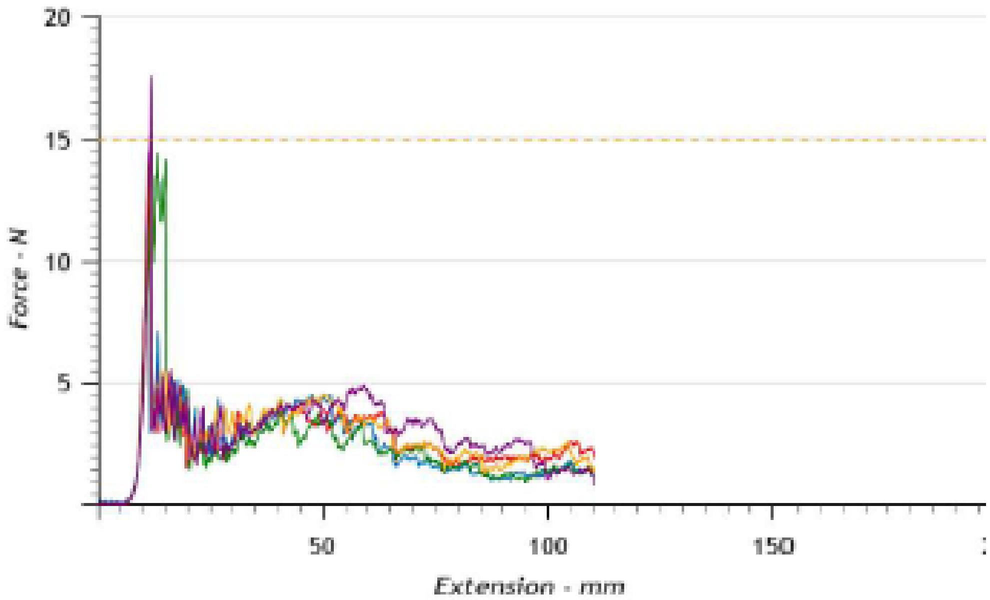
Pull To Extension

Extension: 110.00 mm
Speed: 100.00 mm/min

Results

Specimen	Max Force (N)
1	14.38
2	13.30
3	15.25
4	14.19
5	17.49
Mean	14.92
Conf Limits	±1.98
Coeff Of Var	10.68%

Graph



Appendix 18: Test report for the knife with a curved spine in the weft direction at 2000mm/min.

Test Report

Test Details

Test Name:	K18 WEFT 2000	Date:	01/03/2013
Standard:	CB Implement Puncture Test	Required Directions:	n/a
Specimens:	5	Jaw Scheme:	K18

Procedure Settings

Break Detection: 100 %

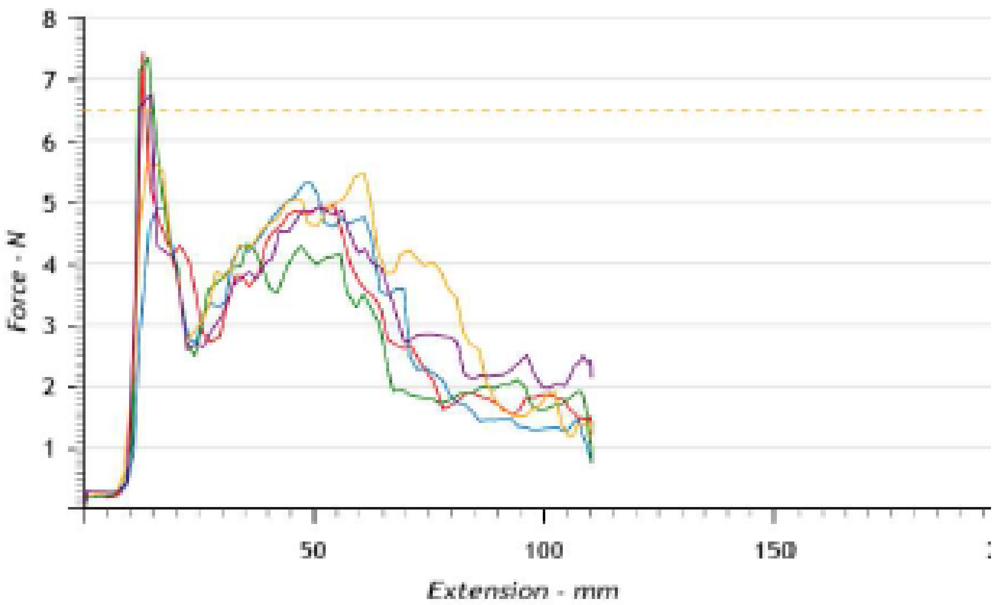
Pull To Extension

Extension: 110.00 mm
Speed: 2000.00 mm/min

Results

Specimen	Max Force (N)
1	7.42
2	5.29
3	7.33
4	5.60
5	6.74
Mean	6.48
Conf Limits	±1.22
Coeff Of Var	15.14%

Graph



Appendix 19: Test report for the knife with a curved spine in the bias direction at 100mm/min.

Test Report

Test Details

Test Name:	K18 BIAS 100	Date:	01/03/2013
Standard:	CB Implement Puncture Test	Required Directions:	n/a
Specimens:	5	Jaw Scheme:	K18

Procedure Settings

Break Detection: 100 %

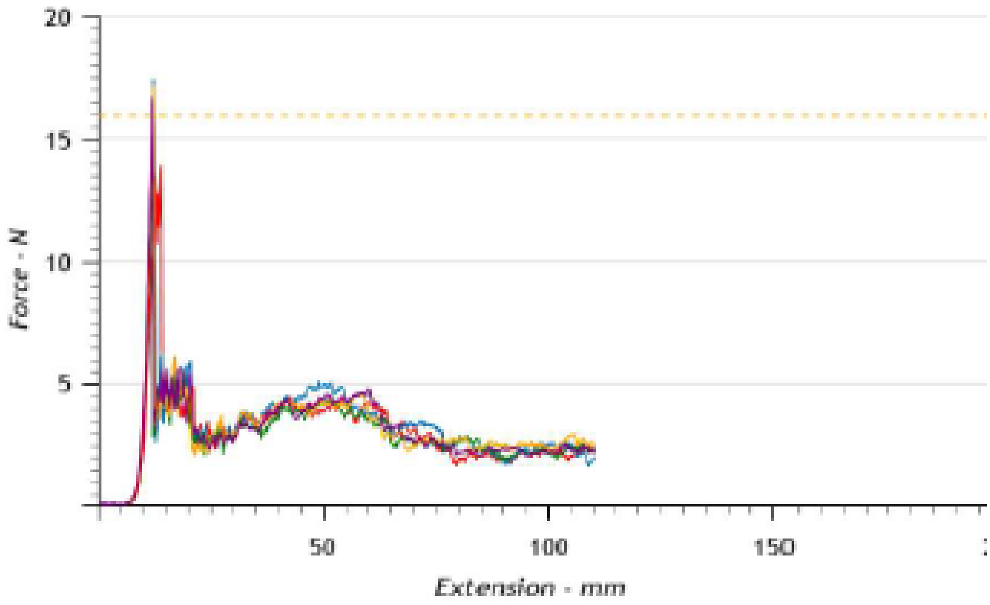
Pull To Extension

Extension: 110.00 mm
Speed: 100.00 mm/min

Results

Specimen	Max Force (N)
1	13.87
2	17.37
3	14.49
4	17.12
5	16.65
Mean	15.90
Conf Limits	±1.99
Coeff Of Var	10.10%

Graph



Appendix 20: Test report for the knife with a curved spine in the bias direction at 2000mm/min.

Test Report

Test Details

Test Name:	K18 BIAS 2000	Date:	01/03/2013
Standard:	CB Implement Puncture Test	Required Directions:	n/a
Specimens:	5	Jaw Scheme:	K18

Procedure Settings

Break Detection: 100 %

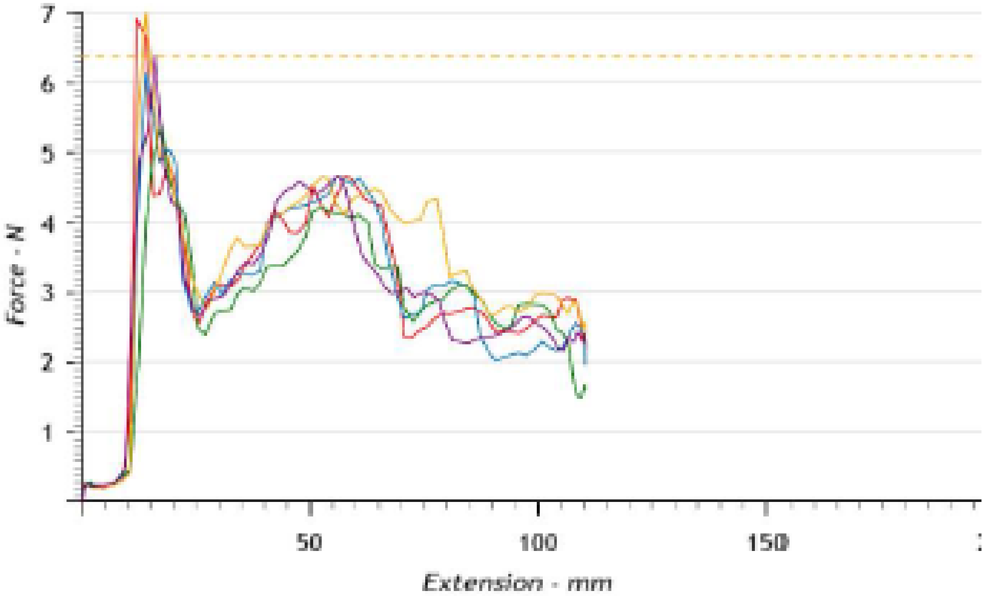
Pull To Extension

Extension: 110.00 mm
Speed: 2000.00 mm/min

Results

Specimen	Max Force (N)
1	6.91
2	6.14
3	5.38
4	6.99
5	6.38
Mean	6.36
Conf Limits	±0.81
Coeff Of Var	10.31%

Graph



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Appendix 21: Test report for the knife with a curved spine into paper at 100mm/min.

Test Report

Test Details

Test Name:	K18 PAPER 100	Date:	26/04/2013
Standard:	CB Implement Puncture Test	Jaw Scheme:	K18
Specimens:	5	Jaw Separation:	99.31 mm
Required Directions:	n/a		

Procedure Settings

Break Detection: 100 %

Pull To Extension

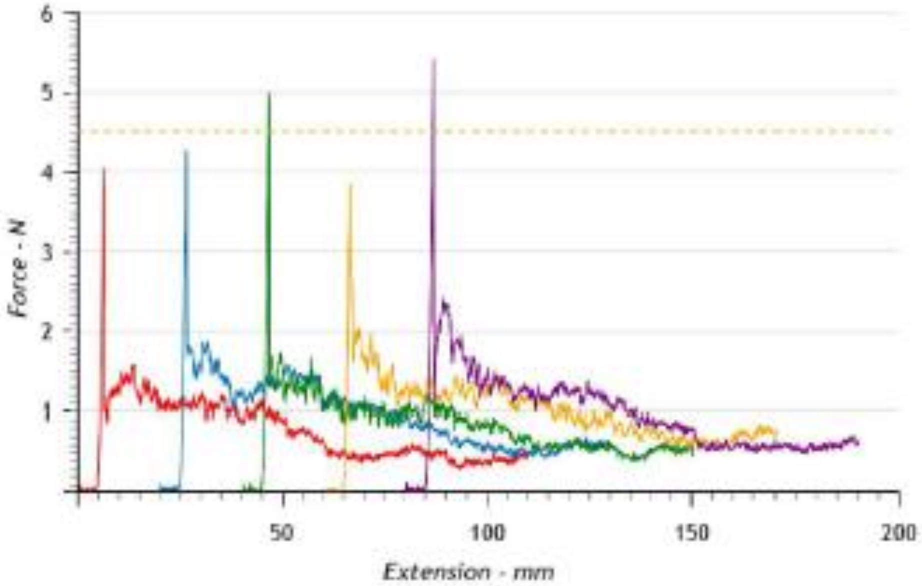
Extension: 110.00 mm
Speed: 100.00 mm/min

Results

Specimen	Max Force (N)
1	4.03
2	4.25
3	4.98
4	3.83
5	5.39
Mean	4.50
Conf Limits	±0.82
Coeff Of Var	14.77%

Appendix 21: Test report for the knife with a curved spine into paper at 100mm/min.

Graph



Appendix 22: Test report for the knife with a double edged blade in the warp direction at 100mm/min.

Test Report

Test Details

Test Name:	K10 WARP 100	Date:	15/02/2013
Standard:	CB Implement Puncture Test	Required Directions:	n/a
Specimens:	5	Jaw Scheme:	K10

Procedure Settings

Break Detection: 100 %

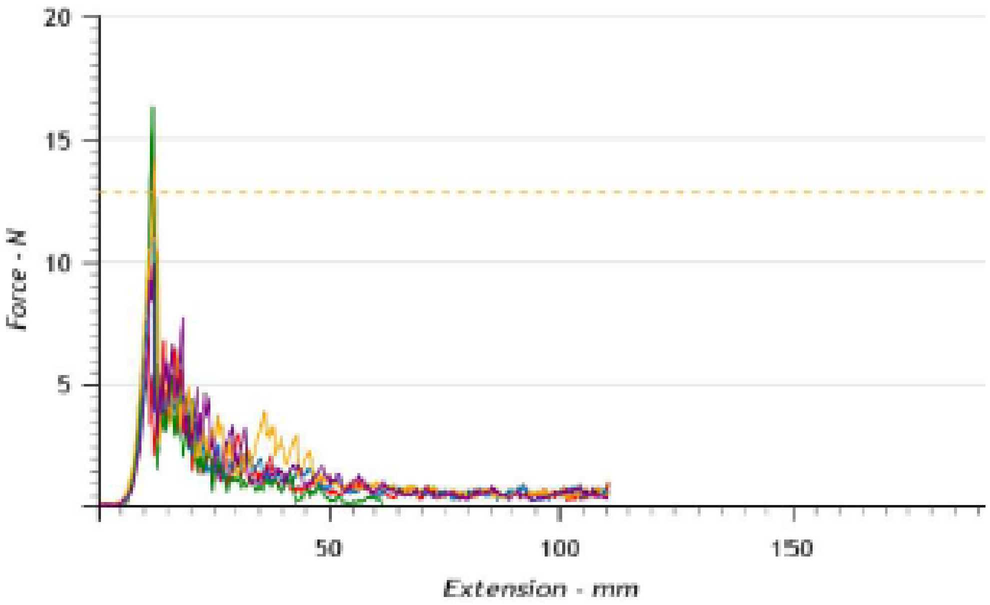
Pull To Extension

Extension: 110.00 mm
Speed: 100.00 mm/min

Results

Specimen	Max Force (N)
1	9.30
2	14.29
3	16.27
4	14.15
5	9.88
Mean	12.78
Conf Limits	±3.76
Coeff Of Var	23.75%

Graph



Appendix 23: Test report for the knife with a double edged blade in the warp direction at 20000mm/min.

Test Report

Test Details

Test Name:	K10 WARP 2000	Date:	15/02/2013
Standard:	CB Implement Puncture Test	Required Directions:	n/a
Specimens:	5	Jaw Scheme:	K10

Procedure Settings

Break Detection: 100 %

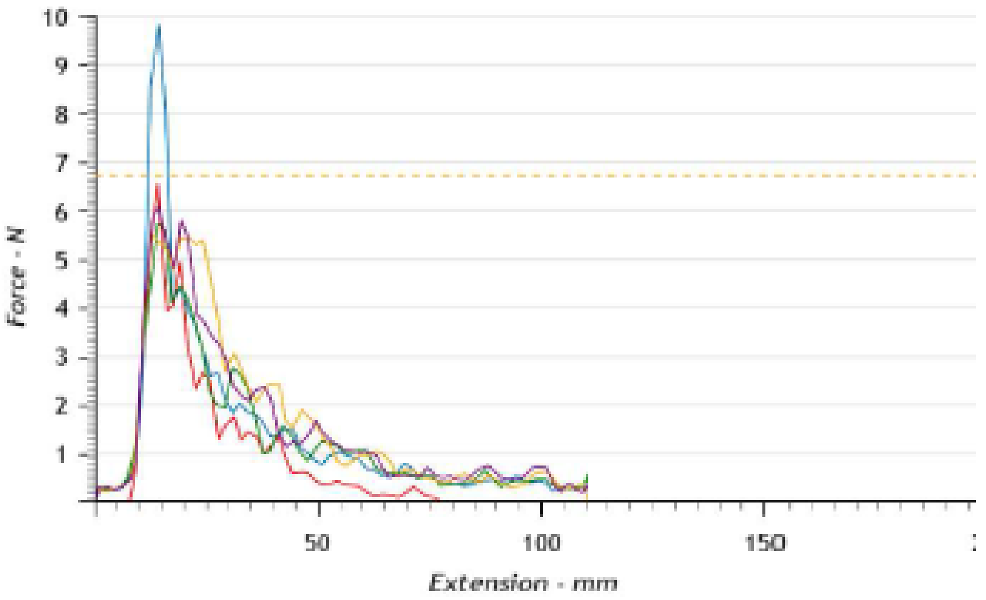
Pull To Extension

Extension: 110.00 mm
Speed: 2000.00 mm/min

Results

Specimen	Max Force (N)
1	6.52
2	9.79
3	5.70
4	5.51
5	6.06
Mean	6.72
Conf Limits	±2.18
Coeff Of Var	26.22%

Graph



Appendix 24: Test report for the knife with a double edged blade in the weft direction at 100mm/min.

Test Report

Test Details

Test Name:	K10 WEFT 100	Date:	15/02/2013
Standard:	CB Implement Puncture Test	Required Directions:	n/a
Specimens:	5	Jaw Scheme:	K10

Procedure Settings

Break Detection: 100 %

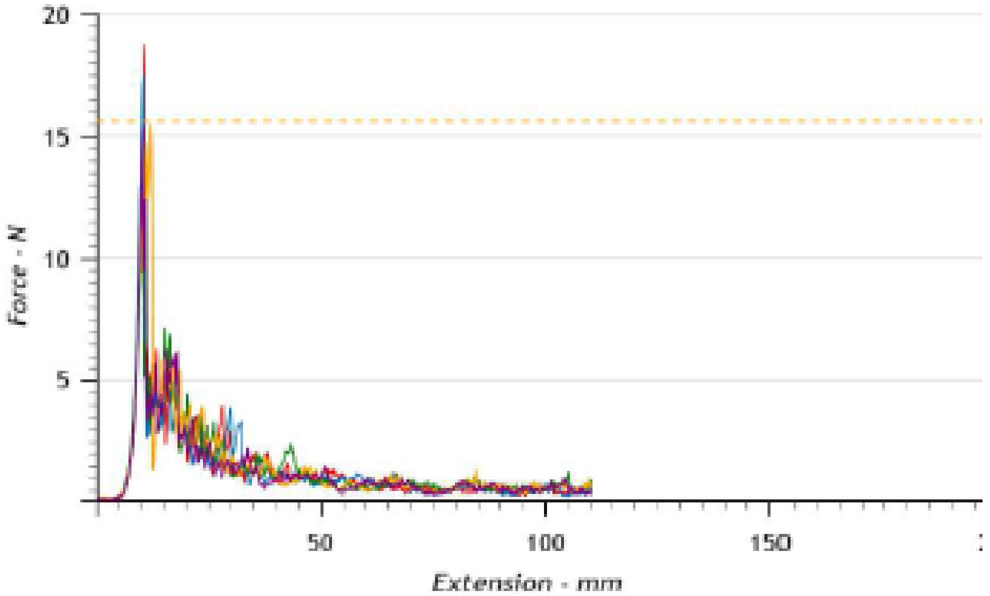
Pull To Extension

Extension: 110.00 mm
Speed: 100.00 mm/min

Results

Specimen	Max Force (N)
1	18.67
2	17.48
3	11.07
4	15.41
5	15.26
Mean	15.58
Conf Limits	±3.59
Coeff Of Var	18.61%

Graph



Appendix 25: Test report for the knife with a double edged blade in the weft direction at 2000mm/min.

Test Report

Test Details

Test Name:	K10 WEFT 2000	Date:	15/02/2013
Standard:	CB Implement Puncture Test	Required Directions:	n/a
Specimens:	5	Jaw Scheme:	K10

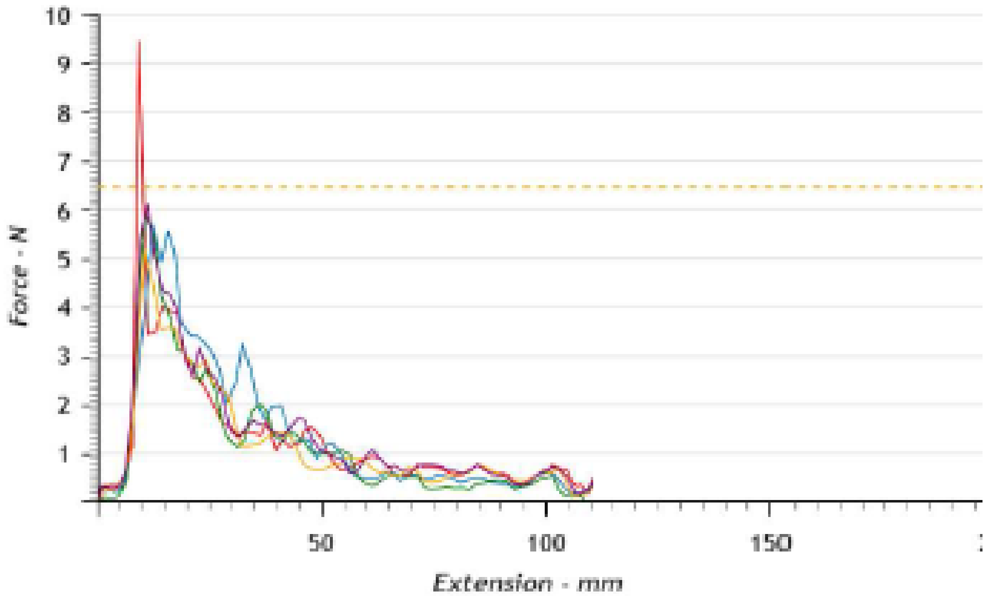
Procedure Settings

Break Detection:	100 %
Pull To Extension	
Extension:	110.00 mm
Speed:	2000.00 mm/min

Results

Specimen	Max Force (N)
1	9.43
2	5.66
3	5.91
4	5.15
5	6.09
Mean	6.45
Conf Limits	±2.11
Coeff Of Var	26.41%

Graph



Appendix 26: Test report for the knife with a double edged blade in the bias direction at 100mm/min.

Test Report

Test Details

Test Name:	K10 BIAS 100	Date:	15/02/2013
Standard:	CB Implement Puncture Test	Required Directions:	n/a
Specimens:	5	Jaw Scheme:	K10

Procedure Settings

Break Detection: 100 %

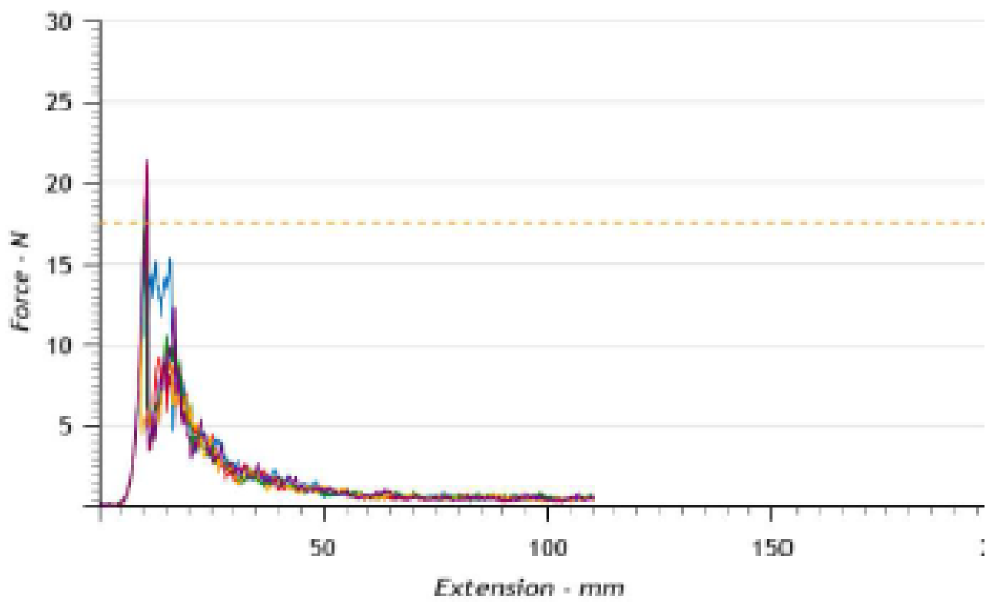
Pull To Extension

Extension: 110.00 mm
Speed: 100.00 mm/min

Results

Specimen	Max Force (N)
1	21.06
2	15.77
3	18.21
4	11.12
5	21.32
Mean	17.50
Conf Limits	±5.24
Coeff Of Var	24.15%

Graph



Appendix 27: Test report for the knife with a double edged blade in the bias direction at 2000mm/min.

Test Report

Test Details

Test Name:	K10 BIAS 2000	Date:	15/02/2013
Standard:	CB Implement Puncture Test	Required Directions:	n/a
Specimens:	5	Jaw Scheme:	K10

Procedure Settings

Break Detection: 100 %

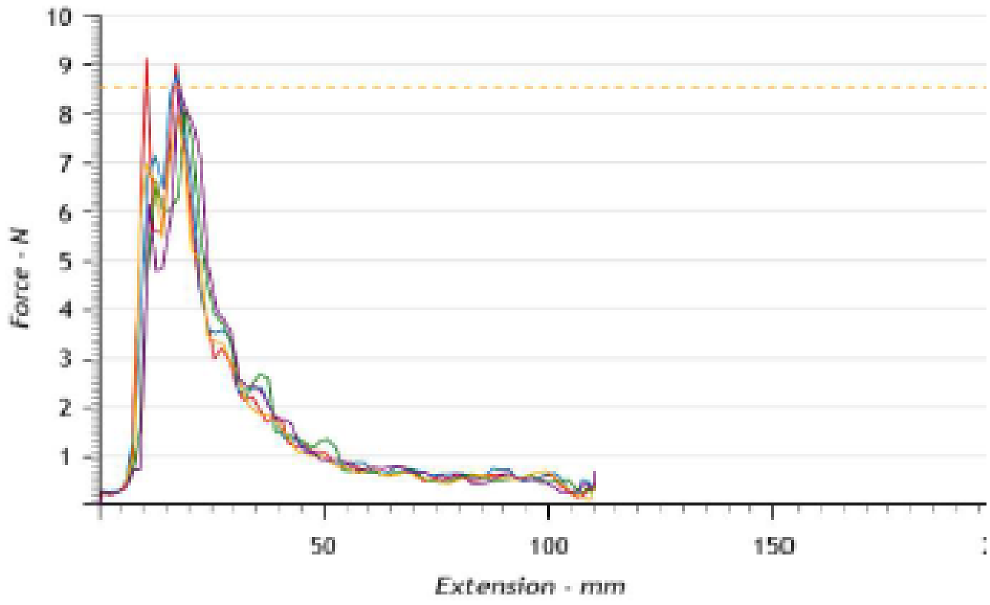
Pull To Extension

Extension: 110.00 mm
Speed: 2000.00 mm/min

Results

Specimen	Max Force (N)
1	9.12
2	8.79
3	8.09
4	7.95
5	8.64
Mean	8.52
Conf Limits	±0.61
Coeff Of Var	5.74%

Graph



Appendix 28: Test report for the knife with a double edged blade into paper at 100mm/min.

Test Report

Test Details

Test Name:	K10 PAPER 100	Date:	23/11/2012
Standard:	CB Implement Puncture Test	Jaw Scheme:	K10
Specimens:	5	Jaw Separation:	5.04 mm
Required Directions:	n/a		

Procedure Settings

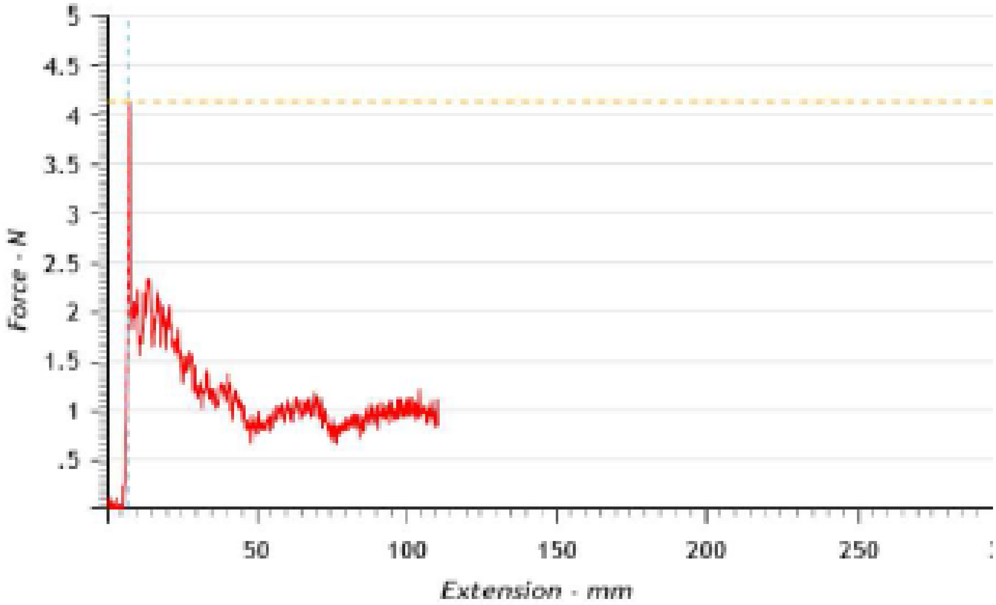
Pull To Extension

Extension:	110.00 mm
Speed:	100.00 mm/min

Results

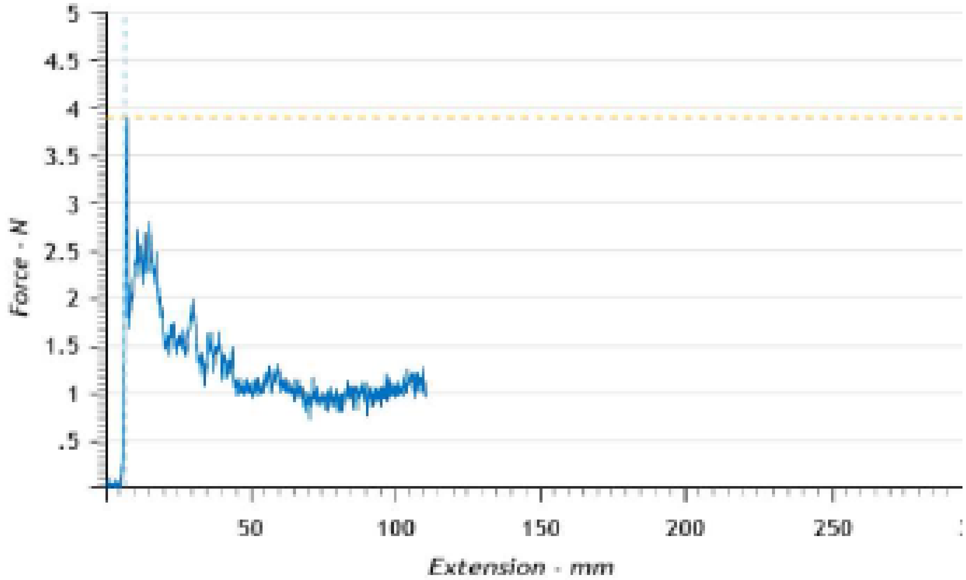
Specimen	Max Force (N)
1	4.12
2	3.89
3	3.90
4	3.62
5	3.73
Mean	3.85
Conf Limits	±0.24
Coeff Of Var	5.00%

Specimen 1 Graph

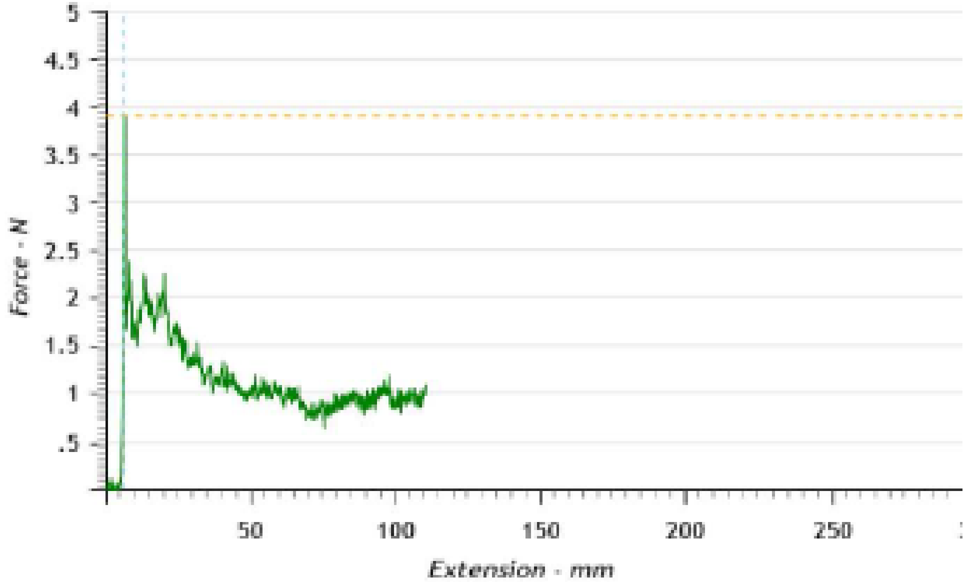


Appendix 28: Test report for the knife with a double edged blade into paper at 100mm/min.

Specimen 2 Graph

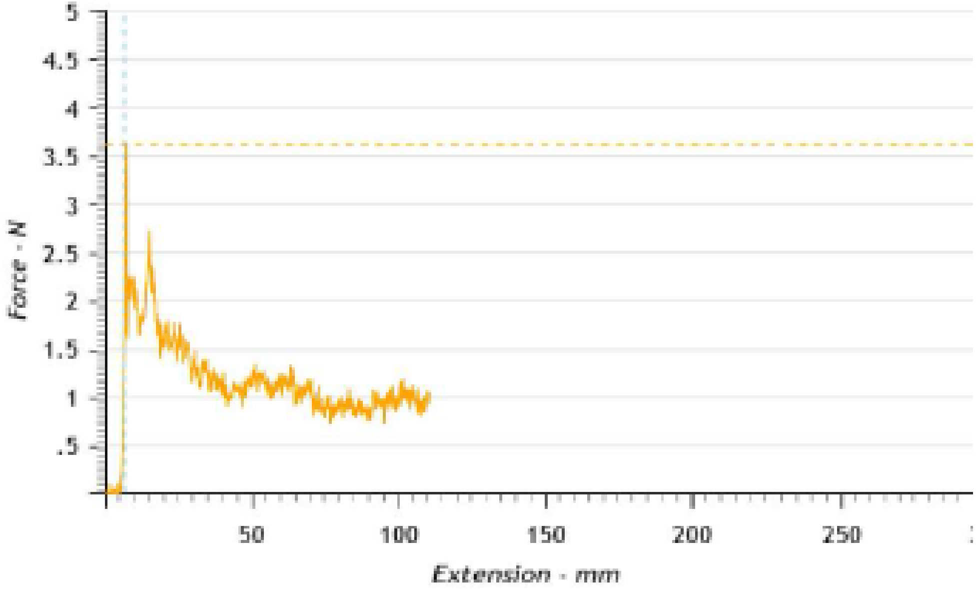


Specimen 3 Graph

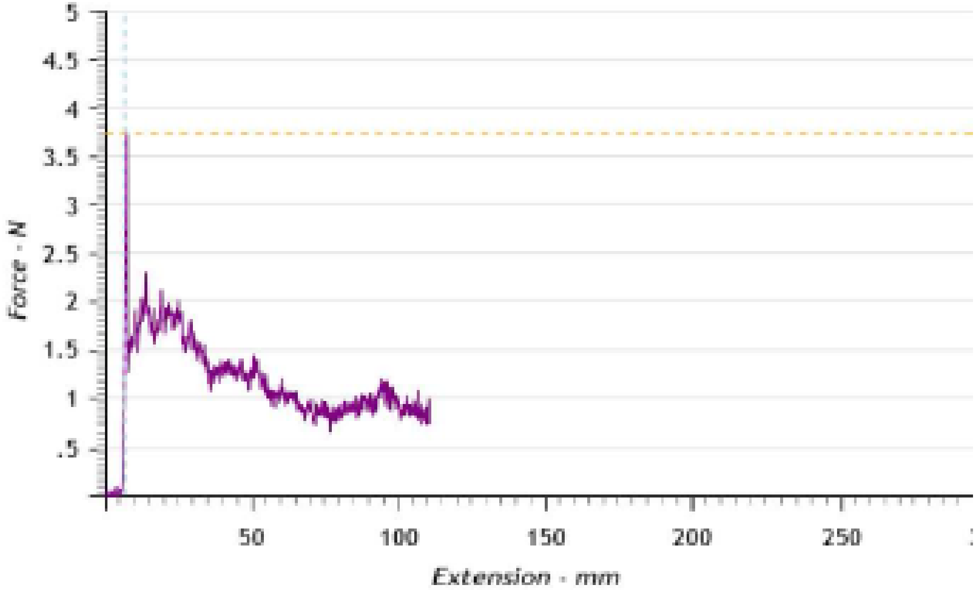


Appendix 28: Test report for the knife with a double edged blade into paper at 100mm/min.

Specimen 4 Graph



Specimen 5 Graph



Appendix 29: Test report for the slotted head screwdriver drill bit in the warp direction at 100mm/min.

Test Report

Test Details

Test Name:	SL6 WARP 100	Date:	11/01/2013
Standard:	CB Implement Puncture Test	Required Directions:	n/a
Specimens:	5	Jaw Scheme:	SL6

Procedure Settings

Break Detection: 100 %

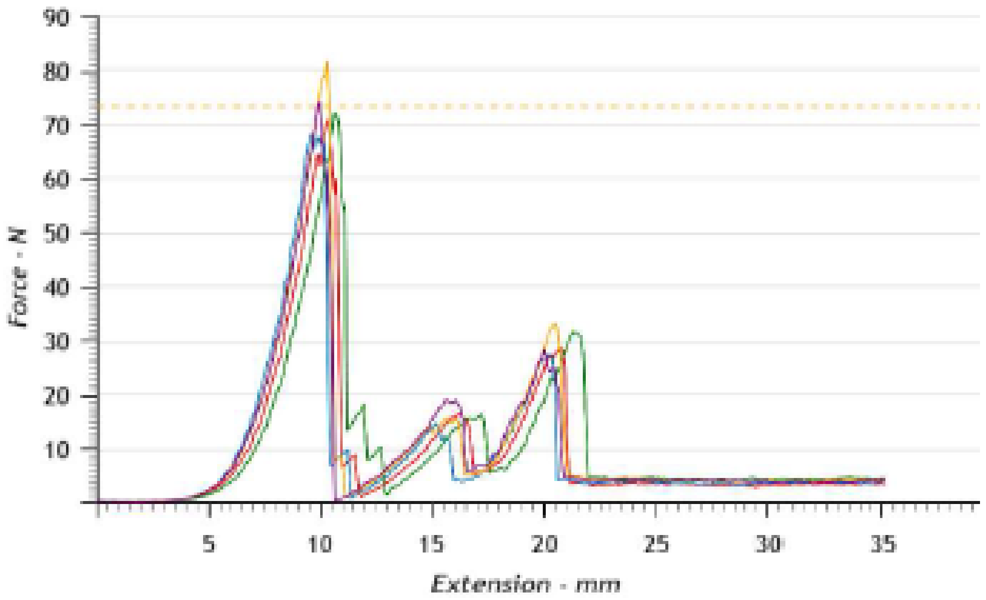
Pull To Extension

Extension: 35.00 mm
Speed: 100.00 mm/min

Results

Specimen	Max Force (N)
1	70.93
2	67.91
3	71.88
4	81.42
5	73.98
Mean	73.22
Conf Limits	±6.30
Coeff Of Var	6.94%

Graph



Appendix 30: Test report for the slotted head screwdriver drill bit in the warp direction at 2000mm/min.

Test Report

Test Details

Test Name:	SL6 WARP 2000	Date:	11/01/2013
Standard:	CB Implement Puncture Test	Required Directions:	n/a
Specimens:	4	Jaw Scheme:	SL6

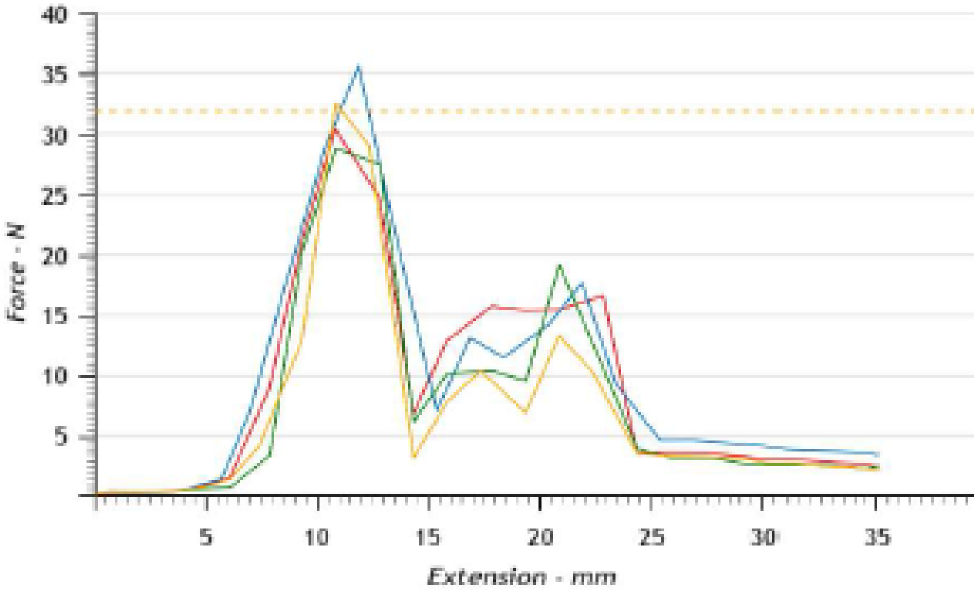
Procedure Settings

Break Detection:	100 %
Pull To Extension	
Extension:	35.00 mm
Speed:	2000.00 mm/min

Results

Specimen	Max Force (N)
1	30.36
2	35.59
3	28.73
4	32.51
Mean	31.80
Conf Limits	±4.72
Coeff Of Var	9.32%

Graph



Appendix 31: Test report for the slotted head screwdriver drill bit in the weft direction at 100mm/min.

Test Report

Test Details

Test Name:	SL6 WEFT 100	**Date:**	11/01/2013
Standard:	CB Implement Puncture Test	**Required Directions:**	n/a
Specimens:	4	**Jaw Scheme:**	SL6

Procedure Settings

Break Detection: 100 %

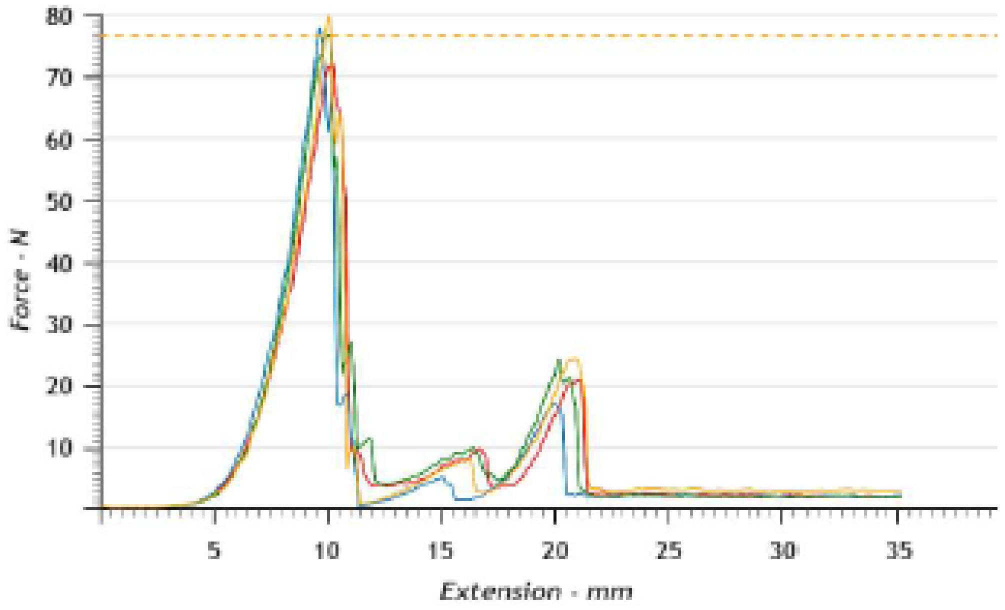
Pull To Extension

Extension: 35.00 mm
Speed: 100.00 mm/min

Results

Specimen	Max Force (N)
1	72.35
2	77.68
3	76.77
4	79.71
Mean	76.63
Conf Limits	±4.94
Coeff Of Var	4.05%

Graph



Appendix 32: Test report for the slotted head screwdriver drill bit in the weft direction at 2000mm/min.

Test Report

Test Details

Test Name:	SL6 WEFT 2000	Date:	11/01/2013
Standard:	CB Implement Puncture Test	Required Directions:	n/a
Specimens:	5	Jaw Scheme:	SL6

Procedure Settings

Break Detection: 100 %

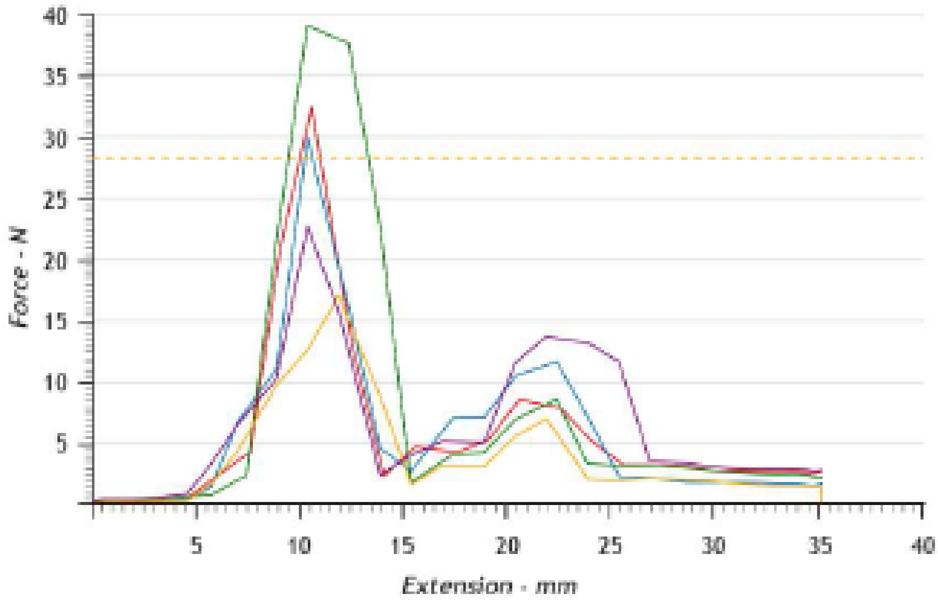
Pull To Extension

Extension: 35.00 mm
Speed: 2000.00 mm/min

Results

Specimen	Max Force (N)
1	32.40
2	29.82
3	39.06
4	17.00
5	22.60
Mean	28.18
Conf Limits	±10.64
Coeff Of Var	30.47%

Graph



Appendix 33: Test report for the slotted head screwdriver drill bit in the bias direction at 100mm/min.

Test Report

Test Details

Test Name:	SL6 BIAS 100	Date:	11/01/2013
Standard:	CB Implement Puncture Test	Required Directions:	n/a
Specimens:	5	Jaw Scheme:	SL6

Procedure Settings

Break Detection: 100 %

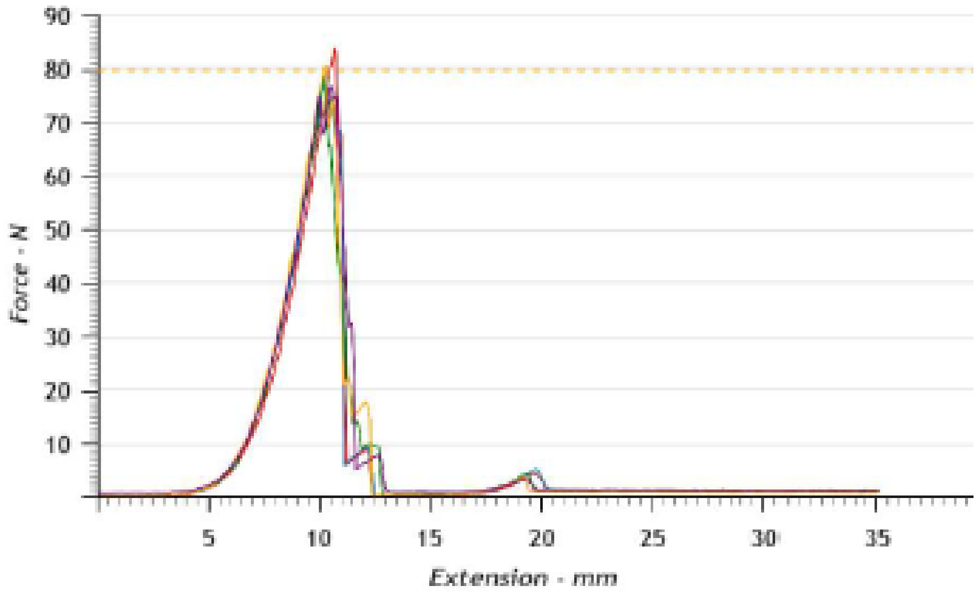
Pull To Extension

Extension: 35.00 mm
Speed: 100.00 mm/min

Results

Specimen	Max Force (N)
1	83.62
2	79.24
3	78.10
4	80.31
5	76.41
Mean	79.54
Conf Limits	±3.35
Coeff Of Var	3.40%

Graph



Appendix 34: Test report for the slotted head screwdriver drill bit in the bias direction at 2000mm/min.

Test Report

Test Details

Test Name:	SL6 BIAS 2000	Date:	11/01/2013
Standard:	CB Implement Puncture Test	Required Directions:	n/a
Specimens:	5	Jaw Scheme:	SL6

Procedure Settings

Break Detection: 100 %

Pull To Extension

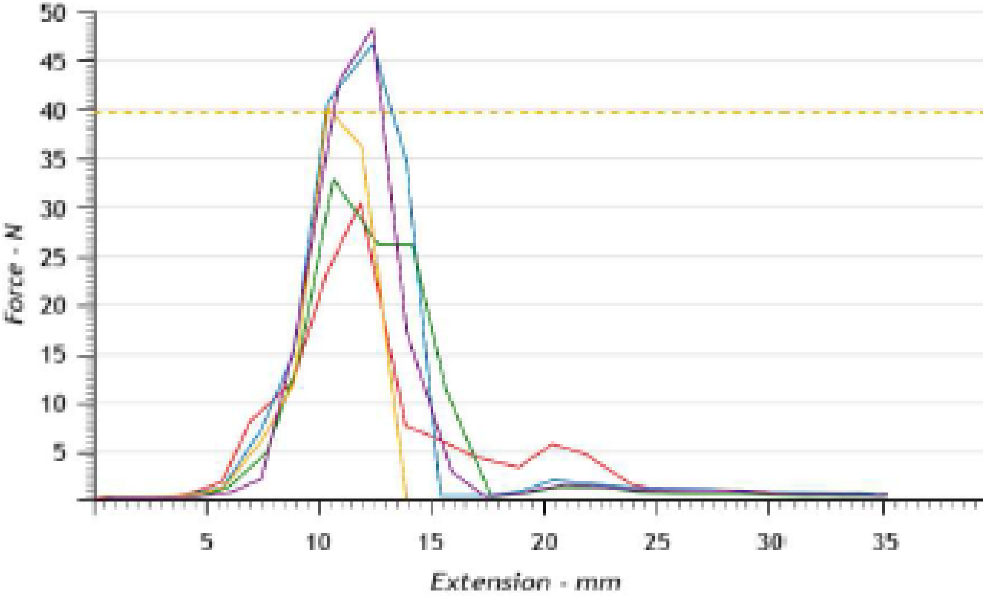
Extension: 35.00 mm

Speed: 2000.00 mm/min

Results

Specimen	Max Force (N)
1	30.35
2	46.55
3	32.79
4	40.06
5	48.18
Mean	39.58
Conf Limits	±9.88
Coeff Of Var	20.13%

Graph



Appendix 35: Test report for the slotted head screwdriver drill bit into paper at 100mm/min.

Test Report

Test Details

Test Name:	SL6 PAPER 100	Date:	11/01/2013
Standard:	CB Implement Puncture Test	Required Directions:	n/a
Specimens:	5	Jaw Scheme:	SL6

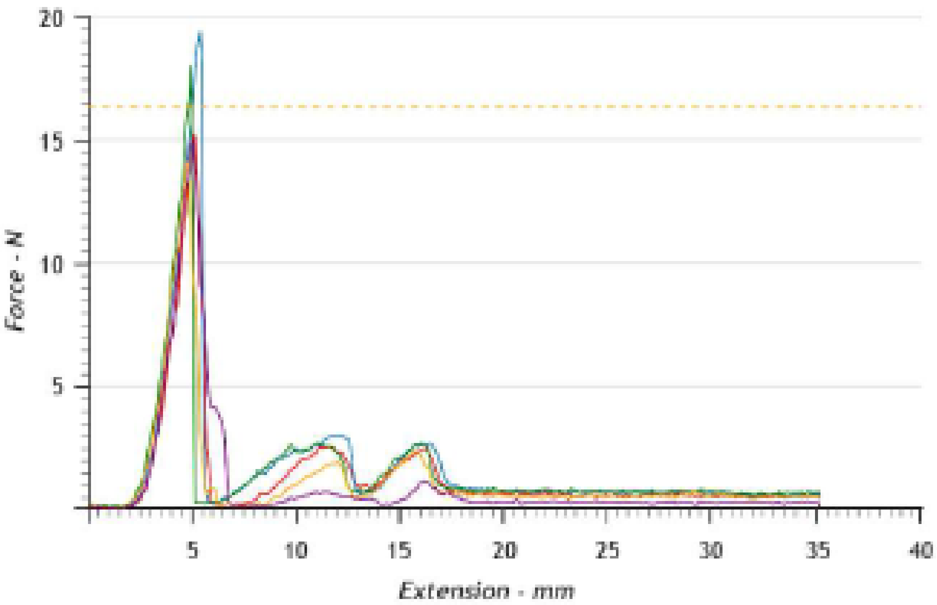
Procedure Settings

Break Detection:	100 %
Pull To Extension	
Extension:	35.00 mm
Speed:	100.00 mm/min

Results

Specimen	Max Force (N)
1	15.16
2	19.35
3	17.97
4	14.04
5	14.96
Mean	16.30
Conf Limits	±2.79
Coeff Of Var	13.82%

Graph



Appendix 38: Test report for the cross head screwdriver drill bit in the warp direction at 100mm/min.

Test Report

Test Details

Test Name:	PH3 WARP 100	Date:	15/02/2013
Standard:	CB Implement Puncture Test	Required Directions:	n/a
Specimens:	5	Jaw Scheme:	PH3

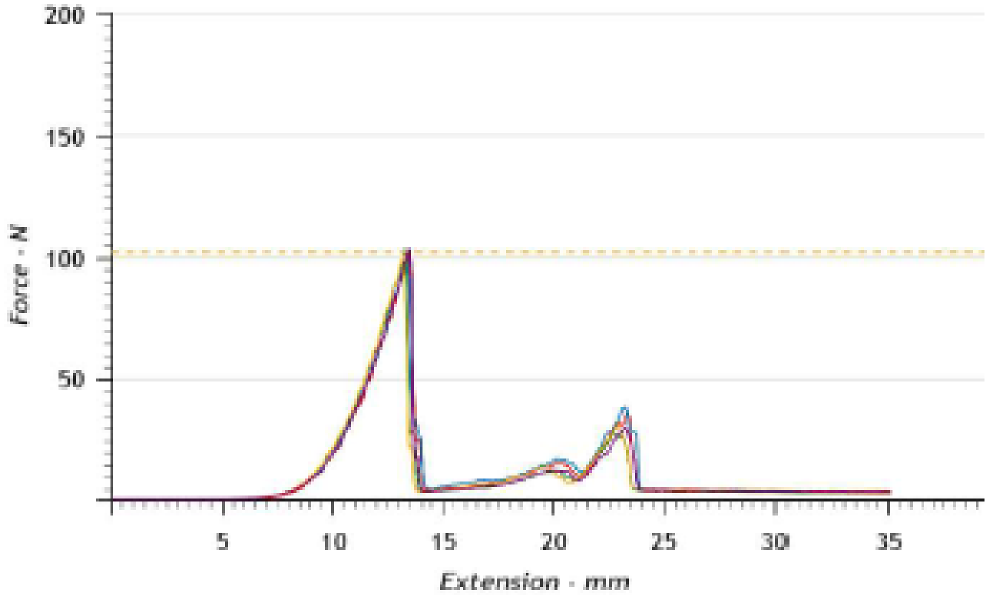
Procedure Settings

Break Detection:	100 %
Pull To Extension	
Extension:	35.00 mm
Speed:	100.00 mm/min

Results

Specimen	Max Force (N)
1	102.30
2	99.72
3	103.21
4	100.12
5	102.82
Mean	101.63
Conf Limits	±1.99
Coeff Of Var	1.58%

Graph



Appendix 37: Test report for the cross head screwdriver drill bit in the warp direction at 2000mm/min.

Test Report

Test Details

Test Name:	PH3 WARP 2000	Date:	15/02/2013
Standard:	CB Implement Puncture Test	Required Directions:	n/a
Specimens:	5	Jaw Scheme:	PH3

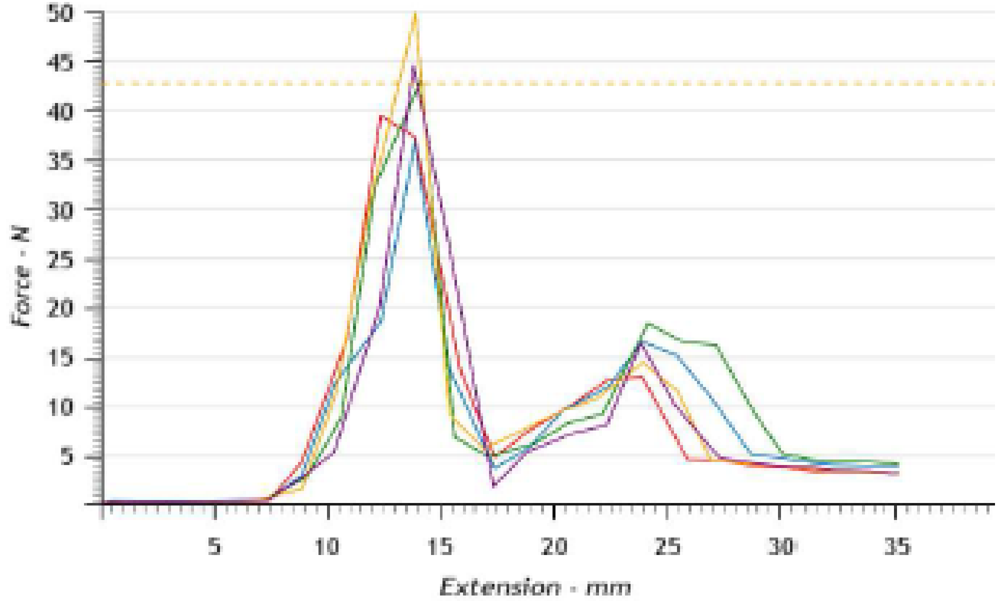
Procedure Settings

Break Detection:	100 %
Pull To Extension	
Extension:	35.00 mm
Speed:	2000.00 mm/min

Results

Specimen	Max Force (N)
1	39.39
2	36.74
3	42.95
4	49.82
5	44.46
Mean	42.67
Conf Limits	±6.21
Coeff Of Var	11.73%

Graph



Appendix 38: Test report for the cross head screwdriver drill bit in the bias direction at 100mm/min.

Test Report

Test Details

Test Name:	PH3 BIAS 100	Date:	15/02/2013
Standard:	CB Implement Puncture Test	Required Directions:	n/a
Specimens:	5	Jaw Scheme:	PH3

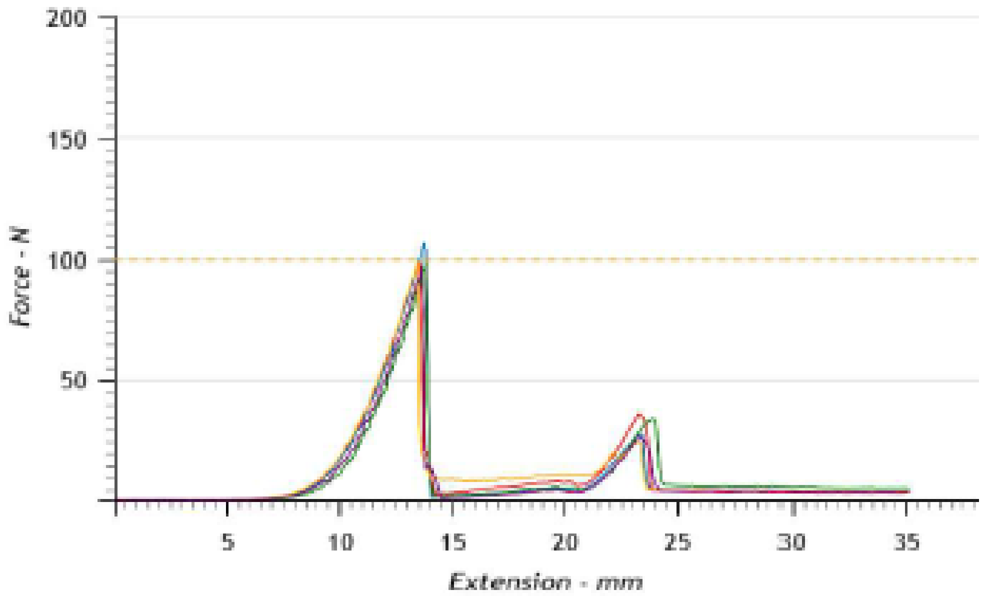
Procedure Settings

Break Detection:	100 %
Pull To Extension	
Extension:	35.00 mm
Speed:	100.00 mm/min

Results

Specimen	Max Force (N)
1	98.31
2	106.38
3	97.50
4	98.47
5	96.85
Mean	99.50
Conf Limits	±4.84
Coeff Of Var	3.92%

Graph



Appendix 39: Test report for the cross head screwdriver drill bit in the bias direction at 2000mm/min.

Test Report

Test Details

Test Name:	PH3 BIAS 2000	Date:	15/02/2013
Standard:	CB Implement Puncture Test	Required Directions:	n/a
Specimens:	5	Jaw Scheme:	PH3

Procedure Settings

Break Detection: 100 %

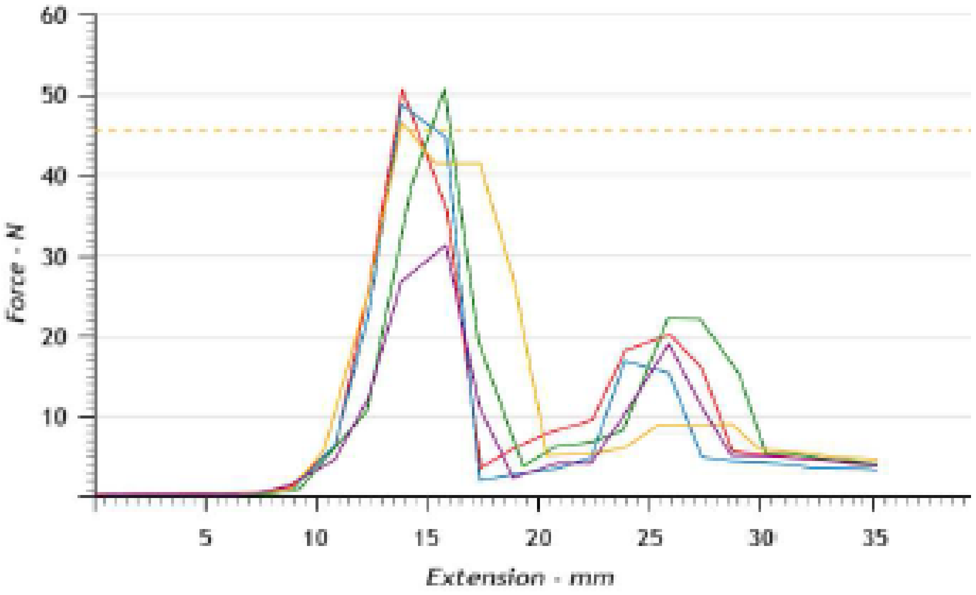
Pull To Extension

Extension: 35.00 mm
Speed: 2000.00 mm/min

Results

Specimen	Max Force (N)
1	50.50
2	48.62
3	50.62
4	46.46
5	31.18
Mean	45.48
Conf Limits	±10.13
Coeff Of Var	17.97%

Graph



Appendix 40: Test report for the cross head screwdriver drill bit into paper at 100mm/min.

Test Report

Test Details

Test Name:	Paper Reference	Date:	15/02/2013
Customer:		Required Directions:	n/a
Standard:	CB Implement Puncture Test	Jaw Scheme:	PH3
Specimens:	5		

Procedure Settings

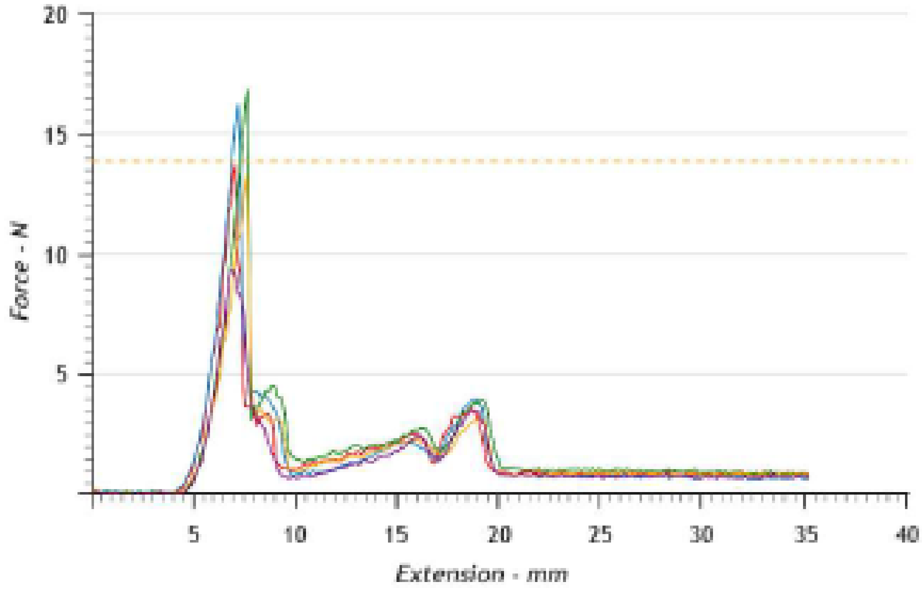
Break Detection:	100 %
Pull To Extension	
Extension:	35.00 mm
Speed:	100.00 mm/min

Results

Specimen	Max Force (N)
1	13.62
2	16.16
3	16.76
4	13.23
5	9.25
Mean	13.81
Conf Limits	±3.69
Coeff Of Var	21.55%

Appendix 40: Test report for the cross head screwdriver drill bit into paper at 100mm/min.

Graph



Appendix 41: Stab cut lengths from the stabbing force experiment

BREADKNIFE (CODE: K1). MAXIMUM BLADE WIDTH: 25mm

Cut widths (mm)	PAPER	WARP 100	WARP 2000	WEFT 100	WEFT 2000	BIAS 100	BIAS 2000
1	25.5	23	23	22.5	22.5	22.5	21
2	25.5	23	23	23	23	23	22.5
3	25	23	23	22.5	22	22	22
4	24	23	23	22.5	23	22.5	22
5	25.5	23	23	22.5	22.5	22.5	22
MEAN	25.1	23	23	22.6	22.6	22.5	21.9
STDEV	0.6519202	0	0	0.223607	0.41833	0.353553	0.547723
CoV	2.5972918	0	0	0.989411	1.851018	1.571348	2.501016
CUT AS A ERCENTAGE OF KNIFE WIDTH	100.4	92	92	90.4	90.4	90	87.6

KNIFE WITH A STRAIGHT SPINE (CODE: K5). MAXIMUM BLADE WIDTH: 18.5mm

Cut widths (mm)	PAPER	WARP 100	WARP 2000	WEFT 100	WEFT 2000	BIAS 100	BIAS 2000
1	20	18	18.5	17	18	17.5	17.5
2	19	18	18	17.5	18	17.5	17.5
3	20	17.5	18	17.5	17.5	17.5	17.5
4	19.5	18	18	18	18	17.5	17.5
5	20	18.5	18.5	17.5	18	17.5	17.5
MEAN	19.7	18	18.2	17.5	17.9	17.5	17.5
STDEV	0.4472136	0.3535534	0.2738613	0.353553	0.223607	0	0
CoV	2.2701198	1.9641855	1.5047323	2.020305	1.2492	0	0
CUT AS A PERCENTAGE OF KNIFE WIDTH	106.48649	97.297297	98.378378	94.59459	96.75676	94.59459	94.59459

KNIFE WITH A CURVED SPINE (CODE: K18). MAXIMUM BLADE WIDTH: 19.5mm

Cut widths (mm)	PAPER	WARP 100	WARP 2000	WEFT 100	WEFT 2000	BIAS 100	BIAS 2000
1	20.5	20	20	19.5	20	18	19
2	20.5	20	20	19.5	20	18	19.5
3	20.5	20	20.5	19.5	20	19	19.5
4	20.5	19.5	21	19.5	19.5	19	19.5
5	20.5	20	21	19.5	19.5	19	19.5
MEAN	20.5	19.9	20.5	19.5	19.8	18.6	19.4
STDEV	0	0.2236068	0.5	0	0.273861	0.547723	0.223607
CoV	0	1.1236523	2.4390244	0	1.383138	2.944745	1.152612
CUT AS A PERCENTAGE OF KNIFE WIDTH	105.12821	102.05128	105.12821	100	101.5385	95.38462	99.48718

KNIFE WITH A DOUBLE EDGED BLADE (CODE: K10). MAXIMUM BLADE WIDTH 24mm

Cut widths (mm)	PAPER	WARP 100	WARP 2000	WEFT 100	WEFT 2000	BIAS 100	BIAS 2000
1	24.5	23	22	23	22.5	23	22
2	24.5	23	23.5	23	23	22	23.5
3	24.5	23.125	23.5	23.5	23	22.5	22.5
4	24.5	23.5	23	23.5	23	22.5	22.5
5	24	23	23	23	23.5	22.5	23
MEAN	24.4	23.125	23	23.2	23	22.5	22.7
STDEV	0.2236068	0.2165064	0.6123724	0.273861	0.353553	0.353553	0.570088
CoV	0.9164213	0.9362437	2.6624889	1.180437	1.537189	1.571348	2.5114
CUT AS A PERCENTAGE OF KNIFE WIDTH	101.66667	96.354167	95.833333	96.66667	95.83333	93.75	94.58333

Appendix 42: Observations before weathering – stab cuts from the double edged blade

FRAME	K10 WARP	SHAPE	EXTRA CUTS	YARN PULLED IN
F1 1	30	STRAIGHT	NO	YES
F1 2	25	STRAIGHT	YES	YES
F1 3	25	STRAIGHT	YES	NO
F1 4	24	CURVE	YES	YES
F1 5	25	WAVE	YES	YES
F2 1	17	STRAIGHT	NO	NO
F2 2	26	STRAIGHT	YES	YES
F2 3	23.5	STRAIGHT	YES	YES
F2 4	26	STRAIGHT	YES	NO
F2 5	25	WAVE	NO	YES
F3 1	29	STRAIGHT	NO	YES
F3 2	29	STRAIGHT	YES	YES
F3 3	28	STRAIGHT	YES	YES
F3 4	26	STRAIGHT	YES	YES
F3 5	17	ZIG ZAG	YES	YES

FRAME	K10 BIAS	SHAPE	EXTRA CUTS	YARN PULLED IN
F1 1	17	WAVE	NO	NO
F1 2	16	WAVE	NO	NO
F1 3	16	CURVE	YES	NO
F1 4	13	CURVE	NO	NO
F1 5	13	WAVE	NO	NO
F2 1	13	WAVE	NO	NO
F2 2	16	CURVE	YES	NO
F2 3	16	CURVE	YES	NO
F2 4	25	V	YES	NO
F2 5	8	CURVE	NO	NO
F3 1	19.5	WAVE	NO	NO
F3 2	15	WAVE	NO	NO
F3 3	19	WAVE	YES	NO
F3 4	18	WAVE	YES	NO
F3 5	16	WAVE	NO	NO

Appendix 43: Observations before weathering – stab cuts from the single edged blade

FRAME	K18 WARP CUT LENGTH mm	SHAPE	EXTRA CUTS	YARN PULLED IN
F1 1	24	STRAIGHT	NO	YES
F1 2	21	STR. CRVD TAIL	YES	YES
F1 3	29.5	STRAIGHT	YES	YES
F1 4	28	STRAIGHT	YES	NO
F1 5	27	STRAIGHT	YES	NO
F2 1	22	STR. CRVD TAIL	YES	YES
F2 2	26.5	STR. CRVD TAIL	YES	NO
F2 3	20	STRAIGHT	NO	YES
F2 4	19	STRAIGHT	NO	NO
F2 5	32	STRAIGHT	YES	NO
F3 1	23	STRAIGHT	NO	YES
F3 2	22	STRAIGHT	NO	YES
F3 3	20	STRAIGHT	NO	YES
F3 4	25	STRAIGHT	YES	NO
F3 5	21.5	STRAIGHT	NO	YES

FRAME	K18 BIAS	SHAPE	EXTRA CUTS	YARN PULLED IN
F1 1	21	V	NO	YES
F1 2	21	WAVE	NO	YES
F1 3	21	WAVE	YES	YES
F1 4	21	WAVE	YES	YES
F1 5	22	WAVE	NO	YES
F2 1	8	WAVE	NO	YES
F2 2	21.5	CURVE	YES	YES
F2 3	22.5	WAVE	YES	YES
F2 4	14.5	WAVE	YES	YES
F2 5	25	CURVE	NO	NO
F3 1	19	WAVE	YES	YES
F3 2	23.5	WAVE	YES	YES
F3 3	26	WAVE	YES	NO
F3 4	26	WAVE	YES	YES
F3 5	23	CURVE	YES	YES

Appendix 44: Full weather data for February 2013

. DAY	DATE	TEMPERATURE	Deg.C		. PRECIPITATION mm		. WIND VELOCITY		. WIND DIRECTION	. WEATHER
		. MIN	. MAX	. AVERAGE	0900-	2100-	. MAX	. MEAN	. MOST PREVAILING	. OBSERVATION
MET 274	Feb-13				2100 GMT.	0900 GMT	(Mean velocity) M/S			
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FRIDAY	01/02/13	1.1	8.3	4.5	0.0	0.0	8.6	3.5	SOUTHWEST	
SATURDAY	02/02/13	0.0	5.5	2.9	0.0	0.0	11.8	3.7	SOUTHWEST	
SUNDAY	03/02/13	4.9	10.0	8.5	0.2	2.4	10.8	5.7	SOUTHWEST	
MONDAY	04/02/13	1.1	7.7	3.8	13.4	6.2	11.1	6.2	SOUTHWEST	
TUESDAY	05/02/13	0.5	5.4	3.8	7.2	0.6	14.3	5.9	SOUTHWEST	SNOW
WEDNESDAY	06/02/13	1.0	5.4	3.1	0.0	0.0	10.6	4.2	SOUTHWEST	
THURSDAY	07/02/13	1.5	4.7	3.1	0.0	0.0	4.4	1.1	WEST	
FRIDAY	08/02/13	2.5	7.3	4.4	0.0	0.8	6.0	2.1	SOUTHWEST	
SATURDAY	09/02/13	1.2	5.2	3.5	0.0	2.2	2.5	0.6	SOUTHEAST	
SUNDAY	10/02/13	0.2	3.4	1.4	7.0	0.6	6.3	3.8	EAST	
MONDAY	11/02/13	1.3	3.3	1.9	1.2	0.0	8.6	4.0	EAST	
TUESDAY	12/02/13	-0.8	2.8	1.3	0.0	0.2	3.6	1.0	SOUTHEAST	
WEDNESDAY	13/02/13	0.0	6.6	3.4	2.6	3.0	7.3	3.0	SOUTH	
THURSDAY	14/02/13	5.3	8.8	6.7	0.0	0.0	5.5	2.2	SOUTHWEST	
FRIDAY	15/02/13	0.0	9.4	5.0	0.2	0.0	7.3	1.5	SOUTHWEST	
SATURDAY	16/02/13	-1.0	10.2	4.3	0.0	0.0	4.1	0.5	SOUTHWEST	
SUNDAY	17/02/13	0.0	9.7	4.5	0.2	0.2	4.3	1.0	SOUTH	
MONDAY	18/02/13	-1.9	8.2	2.5	0.0	0.0	3.5	0.8	SOUTHWEST	
TUESDAY	19/02/13	0.9	10.7	5.1	0.2	0.4	6.5	1.8	EAST	
WEDNESDAY	20/02/13	0.5	3.0	1.5	0.0	0.0	7.4	3.8	EAST	
THURSDAY	21/02/13	0.1	2.6	1.1	0.0	0.0	7.3	3.6	EAST	
FRIDAY	22/02/13	0.3	1.8	1.0	0.0	0.0	7.8	3.5	NORTHEAST	
SATURDAY	23/02/13	0.5	2.7	1.6	0.0	0.0	5.6	3.4	EAST	
SUNDAY	24/02/13	1.7	4.6	3.0	0.0	0.0	7.3	3.8	EAST	

Appendix 45: Full weather data for March 2013

. DAY	DATE	TEMPERATURE	Deg. C		.PRECIPITATION mm		. WIND VELOCITY		.WIND DIRECTION	.WEATHER
		. MIN	. MAX	. AVERAGE	0900-	2100-	. MAX	.MEAN	.MOST PREVAILING	. OBSERVATION
MET 275	Mar-13				2100 GMT.	0900 GMT	(Mean velocity) M/S			
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FRIDAY	01/03/13	-0.9	7.8	4.1	0.0	0.0	8.6	3.6	EAST	
SATURDAY	02/03/13	1.9	10.3	5.2	0.0	0.0	4.6	1.3	SOUTHWEST	
SUNDAY	03/03/13	1.3	9.8	5.9	0.0	0.0	3.0	0.8	SOUTH	
MONDAY	04/03/13	-0.6	7.1	2.7	0.0	0.0	4.8	1.1	SOUTHEAST	
TUESDAY	05/03/13	-0.1	6.4	2.9	0.0	0.0	4.4	1.3	EAST	
WEDNESDAY	06/03/13	2.1	5.4	4.5	0.2	2.0	5.8	2.7	EAST	
THURSDAY	07/03/13	4.4	8.4	5.7	0.8	2.6	8.3	5.1	EAST	
FRIDAY	08/03/13	3.6	5.0	4.2	1.2	6.6	7.1	4.6	EAST	
SATURDAY	09/03/13	1.0	3.8	2.2	5.8	2.4	11.3	7.0	NORTHEAST	
SUNDAY	10/03/13	-3.2	3.1	-0.7	0.0	0.0	15.1	10.2	EAST	
MONDAY	11/03/13	-3.3	1.1	-1.6	0.0	0.0	14.9	7.6	EAST	
TUESDAY	12/03/13	0.7	5.9	3.1	0.2	0.0	8.4	3.1	WEST	
WEDNESDAY	13/03/13	-2.2	5.7	1.6	0.0	0.0	8.4	2.3	SOUTHWEST	
THURSDAY	14/03/13	2.6	6.3	4.5	0.0	0.4	7.0	3.3	SOUTHWEST	
FRIDAY	15/03/13	3.2	7.9	4.9	2.2	4.8	6.8	1.4	SOUTHWEST	
SATURDAY	16/03/13	2.1	8.7	4.7	1.4	0.6	6.5	2.1	SOUTH	
SUNDAY	17/03/13	1.7	6.2	3.5	0.0	0.0	4.8	1.4	EAST	
MONDAY	18/03/13	-0.5	4.4	1.8	2.0	0.2	7.0	1.9	EAST	
TUESDAY	19/03/13	1.0	7.1	3.9	0.0	1.0	6.9	3.0	EAST	
WEDNESDAY	20/03/13	-0.9	2.8	1.3	0.4	0.0	5.3	2.0	EAST	
THURSDAY	21/03/13	0.0	4.3	1.9	0.0	0.0	7.6	5.2	EAST	
FRIDAY	22/03/13	-0.9	1.4	-0.1	2.2	0.4	8.8	5.6	EAST	HEAVY SNOW DRIFTING
SATURDAY	23/03/13	-1.2	-0.2	-0.8	0.4	0.0	8.4	6.1	EAST	HEAVY SNOW DRIFTING
SUNDAY	24/03/13	-0.3	2.4	0.8	2.0	0.0	11.1	7.3	EAST	
MONDAY	25/03/13	-0.4	2.3	0.7	2.0	0.0	14.0	8.9	EAST	
TUESDAY	26/03/13	-0.7	2.4	0.6	2.2	0.0	11.0	6.6	EAST	
WEDNESDAY	27/03/13	-0.7	2.1	0.4	1.2	0.0	9.6	5.2	EAST	
THURSDAY	28/03/13	-2.7	4.1	0.8	1.6	0.0	9.4	3.7	EAST	
FRIDAY	29/03/13	-2.0	4.8	1.2	0.0	0.2	7.6	2.8	EAST	
SATURDAY	30/03/13	-4.0	6.3	1.2	0.0	0.0	7.4	2.1	EAST	
SUNDAY	31/03/13	-0.1	6.1	2.5	0.0	0.0	6.4	3.4	EAST	

Appendix 46: Full weather data for April 2013

. DAY	DATE	TEMPERATURE	Deg.C		. PRECIPITATION mm		. WIND VELOCITY		. WIND DIRECTION	. WEATHER
		. MIN	. MAX	. AVERAGE	0900-	2100-	. MAX	. MEAN	. MOST PREVAILING	. OBSERVATION
276	Apr-13				2100 GMT.	0900 GMT	(Mean velocity) M/S			
MONDAY	01/04/13	-0.2	4.8	2.2	0.0	0.0	9.0	4.5	EAST	
TUESDAY	02/04/13	-1.2	6.7	2.8	0.0	0.0	10.3	3.6	EAST	
WEDNESDAY	03/04/13	0.6	8.5	4.1	0.0	0.0	13.5	7.1	EAST	
THURSDAY	04/04/13	0.0	7.0	3.5	0.0	0.0	16.3	7.8	NORTHEAST	
FRIDAY	05/04/13	-0.9	8.1	3.9	0.0	0.0	11.1	4.5	EAST	
SATURDAY	06/04/13	-1.0	11.9	5.3	0.0	0.0	3.4	0.8	SOUTHWEST	
SUNDAY	07/04/13	1.5	11.8	6.0	0.0	0.0	8.5	2.7	EAST	
MONDAY	08/04/13	1.8	7.2	3.9	0.0	0.0	10.3	6.0	EAST	
TUESDAY	09/04/13	2.7	9.1	5.0	0.0	0.0	12.0	4.4	EAST	
WEDNESDAY	10/04/13	2.5	12.9	6.8	0.0	0.0	6.9	3.0	EAST	
THURSDAY	11/04/13	3.3	7.0	4.7	1.0	5.2	5.3	2.0	EAST	
FRIDAY	12/04/13	3.6	11.4	6.8	1.4	0.0	4.1	1.0	SOUTHWEST	
SATURDAY	13/04/13	10.4	16.2	12.6	1.2	0.6	10.8	3.5	SOUTH	
SUNDAY	14/04/13	12.6	16.1	13.1		0.0		5	SOUTHWEST	Data from Paul
MONDAY	15/04/13	11	14.9	10.8		1.2		8.6	SOUTHWEST	Data from Paul
TUESDAY	16/04/13	8.6	13.9	11.8		1.8		5.1	SOUTH	Data from Paul
WEDNESDAY	17/04/13	6.4	14.5	9.6		0.5		5.3	SOUTHWEST	Data from Paul
THURSDAY	18/04/13	6.1	16.2	8		3.6		7.1	SOUTHWEST	Data from Paul
FRIDAY	19/04/13	4.7	13.3	5.3		2.8		3.2	NORTH	Data from Paul
SATURDAY	20/04/13	1.2	11.3	7.1		0.7		1.2	SOUTHWEST	Data from Paul
SUNDAY	21/04/13	4.3	12.1	8.1	0.2	0.0	8.9	2.9	SOUTHWEST	
MONDAY	22/04/13	8.6	14.4	11.1	0.0	0.0	11.5	6.1	SOUTHWEST	
TUESDAY	23/04/13	10.0	15.1	12.3	0.0	0.0	9.0	3.5	SOUTHWEST	
WEDNESDAY	24/04/13	9.7	15.6	11.9	0.0	0.0	8.3	2.1	SOUTHWEST	
THURSDAY	25/04/13	4.8	13.1	8.7	0.6	0.0	6.5	2.3	SOUTHWEST	
FRIDAY	26/04/13	3.4	11.2	7.8	4.2	0.2	8.3	3.8	SOUTHWEST	
SATURDAY	27/04/13	3.8	12.7	6.5		0.0		4.9	NORTHWEST	Data from Paul
SUNDAY	28/04/13	2.8	11.3	8.6		1.2		4.1	NORTHWEST	Data from Paul
MONDAY	29/04/13	5.5	12.3	8.3	0.0	0.0	6.5	3.1	SOUTHWEST	
TUESDAY	30/04/13	4.0	14.3	9.7	0.0	0.0	7.6	1.5	SOUTH	

Appendix 47: Stab cut platform