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Priscilla Reiners

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UNIVERSITÉ DE HAUTE ALSACE
LABORATOIRE DE PHYSIQUE ET MÉCANIQUE TEXTILES

THÈSE

pour obtenir le grade de

DOCTEUR DE L'UNIVERSITÉ DE HAUTE ALSACE
DISCIPLINE : MÉCANIQUE

par

Priscilla REINERS

INVESTIGATION ABOUT THE STAB RESISTANCE OF TEXTILE STRUCTURES, METHODS FOR THEIR TESTING AND IMPROVEMENTS

Soutenue le 29 Septembre 2016 devant le jury suivant:

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LIST OF ABBREVIATIONS

B.C.	Before Christ
CPPT	Cut Protection Performance Tester
E_{KIN}	kinetic energy
E_{POT}	potential energy
F	Force
F_{K}	kinetic force
F_{N}	normal force
F_{S}	static force
G	Gravity
g	gram
h	height
KR	Knife Resistance
ln	Logarithmic
m	mass
N	Newton
nm	Nanometre
P61	Plain weave fabric – 61 g/m ²
P170	Plain weave fabric – 170 g/m ²
P230	Plain weave fabric – 230 g/m ²
PBO	Poly-para-phenylene-2,6-benzo-bisoxazole
PPE	Personal Protective Equipment

PTI	Polizeitechnisches Institut (Technical Institute of the Police department)
R^2	Coefficient of determination
SK	Schutzklassen (Protection classes)
SP	Spike resistance
ST	Stichschutz (Stab resistance)
STF	Shear Thickening Fluid
T170	Twill weave fabric – 170 g/m ²
T230	Twill weave fabric – 230 g/m ²
TR	Technische Richtlinie (Technical guideline)
UD	Unidirectional
UHMWPE	Ultra-high molecular weight Polyethylene
V	Volume
v	velocity
VPAM	Vereinigung der Prüfstellen für angriffshemmende Materialien und Konstruktionen
W	Work (energy)
W_C	Cutting work
W_{FBY}	Work of friction between yarns
W_{FCY}	Work of friction for cutting yarns
W_{PP}	Work for penetration of plasticine
μ	Coefficient of Friction

INTRODUCTION

0 Introduction

David replied to the Philistine: “You are coming against me with sword and spear and javelin, but I am coming against you in the name of Jehovah of armies, the God of the battle line of Israel, whom you have taunted. This very day Jehovah will surrender you into my hand” (1 Samuel 4:45, 46).

In the whole human history, human fought against each other using weapons. One of the first notations, which was written about 1040 B.C., can be found in 1 Samuel 17:4-6 (New World Translation of the Holy Scriptures 2013), mentioning the Philistine Goliath:

Then a champion came out from the camps of the Philistines; his name was Goliath and his height was six cubits and a span. He had a helmet of copper on his head, and he was wearing a coat of mail of overlapping scales. The weight of the copper coat of mail was 5000 shekels. He had shin guards of copper on his legs and a javelin of copper slung between his shoulders.

Only Goliath's coat of mail already reached a weight of 5000 shekels which equates to 57 kilograms. The bible report shows that he was in height six cubits and a span, which is equal to 2.90 meters. Since then, many developments were continued to improve body armour. New materials were developed, which are lighter, more flexible and give a particular protection against attacks. In the modern age, body armour primary was developed in the area of ballistic to protect against bullets, since firearms were invented in the 19th century. But also the protection against sharp edges, such as knives increased in significance since a rise in stab attacks against police or military personnel is increasing. The annual report of the national police in Germany shows, that 6.8% of policemen were attacked in 2014 and 1.8% were injured.

About 2.8% of all criminal offences were personal injuries (Vege sack 2014). The head of the police labour union of North Rhine Westphalia said in a radio interview in August 2015 that every eighty minutes a policeman is attacked in North Rhine-Westphalia. The violence against police members is increasing (BKA NRW 2012). Therefore a high interest of demand of body armour is given.



Figure 0-1: Goliath
(Watchtower Bible and Tract Society 2004)

Modern armour is normally designed to resist against bullets or against knives. The parameters and the comfort vary, in dependency on the protective requirements. To protect against firearms attacks, bulletproof vests are available in different defined protection levels. Against stab attacks, just limited solutions are available. Vests of high protection grades are realizable using steel- or ceramic shields, which are inflexible and heavy. Flexible body armour out of chain-mails with different size links or textile materials gives a restricted protection, it depends on the stab device and the applied energy, if it is penetrated or not. For bulletproof body armour there are defined levels depending on the energy of shot and calibre of the firearm, but in the area of stab protection a definition of a protection level is difficult to realize. A stab mechanism can cause a displacement, cutting or punching, depending if a needle, a sharp knife or an ice peak is used. While there are some stab instruments that can be stopped, there are others that cannot be prevented, depending on knife, assailant, stab event and victim (Scott 2005; New World Translation of the Holy Scriptures 2013). For example, metal foils resist against needles, but not against blades. Fabrics are penetrated by needles but give protection against blades. Also the requirements all over the world are very different. They vary between maximum impact energy of 35 Joule, 42 Joule in Great Britain and 100 Joule in USA and Germany (Fenne 2005). But is the definition of the maximum energy the critical approach to define the best results? A needle for example deforms during a high energy and velocity attack, while a slow motion penetrates the panel. Normally the measurement is done by a free fall of the defined blade into the panel out of a defined height, depending on the required energy. But in reality, the situation of an attack is always different, in some cases the assailant stabs several times while stabbing in different another angles. There are still some questions not answered. To give a satisfying proposition about the protection level, the test methods have to be extended and reworked. Another problem is that a combination of protection against firearms and stab attacks leads necessarily to a higher weight and therefore to a heavier and a more inflexible body armour. That is one reason, why users like policemen, are reluctant to use the combination of both. To improve the comfort and acceptance, it is necessary, that body armour is light and flexible enough, to wear it all day at any weather conditions.

This study analyses the different parameters, which influence the stab performance. In order to pursue these research thoughts by means of empirical studies, some aramid fabrics are tested with different parameters to compare their stab resistance in order to make an evaluation of the influence of varying parameters. Initially a general overview of application

fields is given in which such textiles for protection against mechanical effects such as cut or stab attacks are applied. Then the threats that occur in the case of stab attacks are characterized by analysing the processes and mechanism during a stab attack. A delimitation between stab or puncture and slash attacks is difficult to define, therefore the protection technology against puncture is in the focus, which is explained in a general description of the application of puncture protection products and an analysis of the current state of the art with focus on the materials which are used and their processing and structures. The subsequent methodological part includes a description of the methodological approach based on the description of the test fabric, the measurement setup and the practical experiments, as well as the appropriate presentation and discussion of the results. This study analyses the different parameters which influence the stab performance and compares different test methods to determine these parameters, to represent some of these methods more realistic according to everyday life and to improve some fabric properties.

CHAPTER 1

1 Literature Review

1.1 Body armour- the Personal Protective Equipment PPE

PPE has to cover or replace the every day's clothing to give a certain level of protection against different threats. These textiles for protection determine an important field of research and are also one of the most growing fields for industry and leisure time (Byrne 2000). Body armour is a part of the area of PPE. It protects the body against thermal, chemical or mechanical influences. PPE should protect to a required level and maintain the health, without affecting the natural movements or the circulation of the body. That means, that a good comfort is guaranteed, which encloses, that the PPE is light and flexible and the heat and moisture transport from the body to the environment is given. It is essential, that the PPE is not noticed by the wearer. At the same time it should reduce the risk of injuries. According to the PPE guideline, the PPE has to protect against all defined risks and should be suitable for the given conditions and meet the ergonomic requirements (Directive 1989). Therefore the best compromise between efficiency, comfort and costs have to be found.

There is a variety of PPE that need to protect against different hazards. The most frequent and different kinds of threats for humans are mechanical risks like bullets, knives or rotating machines (Byrne 2000). The cut and puncture resistances are part of these mechanical threats, which mostly occur during attacks on humans. This work focusses on the different danger areas where the puncture and cut protection is applied. In the following, the importance of body armour against puncture and slash threats are presented.

1.2 Common application areas of body armour for stab und slash resistance

Normally it is expected that textiles give no high resistance against cut during production (Reumann 2000). But for some application areas a high cut resistance of textiles is an important factor to protect against unintended or wanton destruction by sharp-edged objects. These textiles have to resist against forces, which occur during the cut processes, to a certain level (Finkelmeyer 2002). Not only cut resistant textiles, but also stab resistant textiles are required for some fields of application (Alpyildiz et al. 2011). The main goal in this application area is to absorb the maximum impact energy to protect human beings against injuries.

In general, stab and slash resistant textiles can be divided in two significant application areas. On the one hand the protection of human beings, in which the textiles protect the human body from threats caused by pointed or sharp-edged objects. On the other hand the protection of objects, where textiles protect objects but also the structures themselves against destruction through stiches or cuts.

1.2.1 Personal protection

Personal protection includes all kinds of protective clothing in the areas of PPE and the sports area. In general, stab-resistant clothing is manufactured, to protect humans against accidental stab wounds and cuts (BGR196). This applies to the whole body, as well as high-risk areas such as hands and arms (BGR200), which means that the wearer is protected during his working sufficiently against cut and stab injuries. In general, personal protective equipment is required for professional groups, who work every day with sharp objects like sharp knives, saws, scissors or other sharp objects. Forest workers are in the exercise of their activities permanently in contact with heavy, sharp saws. Workers in the field of cutting in the textile and clothing industry also use sharp knives, to cut multi-layer fabrics. Especially in the food industry accidents with hand knives are not uncommon. About 30-40% of all accidents occur with hand knives (BGI 2004).

Applications in the sports area for puncture and cut resistant garments are among others for motorcyclists, ski clothing, diving equipment and the fencing clothing (Finkelmeier 2002).

However stab resistant textiles are not only used to prevent accidental stab injuries, but also to protect against unintentional injuries by other people. Another risk group are the employees of the Security Forces, such as police, Special Forces and security services. They also have to be protected against stab and cut injuries adequately, because they are constantly exposed to hazards in their profession, such as attacks with knives or other sharp objects. Protection must be given to these life-threatening hazards. Due to the diverse dangers, protection equipment needs to be adjusted respectively to the threat.

Primarily stab protective vests that protect the torso against serious or fatal dangers are used. Since users mainly come from the police sector the police takes influence on the testing methods or the development of new vests (Scott 2005; Fenne 2005, 2005). There are two different kinds of body armour vests available- one type is worn under the garments and cannot be seen and the other kind of vest is worn visibly on top of the clothing. The armour also differs in the extent of their protection capability. Some models give primarily a ballistic protection against projectiles, where the stab protection panel can optionally be introduced through appropriate stab protection inserts. Another type is a protective vest that combines ballistic and stab protection and the components cannot be separated. In addition to the vest there do exist more body protection equipment, which is used to protect the neck, trunk and extremities. This equipment may consist of several components, which are intended to enable a modular construction and can be worn in various combinations or alone (Damm 1997).

The need is also shown in the increase in violence. Insults of the worst kind, threats and even physical assaults are happening in Job Centres, in customs, in classrooms, social service offices and in many other jobs. And not just from time to time, but often (Peters 2015).

Wearing body armour is necessary if an increased probability of threat is given. This protection means reducing the risk of injury to limit the potential harm. Due to the different threats and numerous weapons, vests are classified into safety classes.

1.2.2 Protection of objects

In this area, objects should be protected against hazardous materials or influences in the fields of work and leisure time. In contrast to the personal protection area, textiles for the protection of objects usually should preserve against destruction themselves. Cut resistant textiles are attempted to reduce the problem of vandalism, which is the main problem in this area (Finkelmeyer 2002). Due to vandalism, in Germany there is a loss of around 1 billion euros each year, which is most often caused by the destruction of objects within public institutions (European Union 2013). Targets of vandalism, which manifests itself in the form of destructive punching or cutting stresses by knives or other sharp objects, are for example seats and upholstery in public transport (Guerth 2015). Other targets of vandalism are on the other hand truck tarpaulins, market stalls, tents and convertible tops, as the textiles in these application areas have to fulfil a protective function against theft actions (Reumann 2000; Finkelmeyer 2002). In particular truck tarpaulins are an area, where optimized solutions for increased puncture and cut resistance are required. About 3000 tons of transporting goods are transported every year in Europe by truck about 60000 of these shipments annually are robbed what brings about a significant economic damage (European Union 2013). In addition to the primary protection against deliberate destruction protective textiles must also offer protection against accidental cutting actions, which are as a secondary function no less relevant. For example truck tarpaulins can be damaged or destroyed by sharp-edged items (Reumann 2000).

Also in the area of sport and leisure items, puncture and cut resistant textiles can be found as applications: inflatable boats can be damaged by sharp rocks or stones or tents, when they stand on sharp-edged surfaces (Finkelmeyer 2002).

1.3 Importance of body armour

PPE with stab and cut protection are required by professional groups, in which the use or contact with sharp knives, saws, scissors or other sharp objects are an everyday occurrence. These areas include among others the forestry sector, the food production sector, such as butcher, or the clothing sector. According to the professional association of industry, about 45% of injuries with hand tools happen with knives (BGI 2004). Only in the food sector 30 - 40% of all accidents happen with knives. Not only accidents but

also intentional injuries with sharp weapons lead to an increased demand for stab resistant body armour (Aromaa, Viljanen 2010).

Another risk group are the employees of the Security Forces, such as the police or security services (Jager 2013; Ohlemacher 2003). They also need to be protected adequately against stiches and cuts. An important group of these were police officers who are in their profession constantly exposed to the danger of attacks by knives and other sharp instruments, which are used as weapons (Scott 2005). The annual report 2014 of the German Federal Police reported 2089 attacks on law enforcement officers. This means, that 6.8% of all police officers were attacked during their work and 1.8% were injured (Vege sack 2014). A study out of the year 2012 showed that just 53.5% of police officers wore their safety vest during an attack and only 36.7% were protected against stab attacks (Ellrich et al. 2012).

Another study in 2009 showed, that 84% of all attacks against police officers were body attacks with the use of violence and 20% of them with weapons (Hunsicker 2015). The protection of the police officer is given only conditionally, since most injuries in the neck and back area occur. Therefore a PPE which protects these areas without limiting the freedom of movement would be desirable (Hunsicker 2015).

Since there have been eight deadly attacks on police officers in NRW, a research project was commissioned in 2000 to test body armour with puncture protection on carrying capacity. After four months of wearing tests the analysis showed, that vests, which are according to the Technical Guidelines for protective vests with integrated puncture justice, bring only a low level of acceptance regarding the wearing comfort of the police officers. Only lightweight jackets with a partial puncture gained a higher popularity, however they are not according to the highest possible protection class (Lorei 2001).

The development of appropriate protective equipment should therefore be adapted to a large extent to the needs of police officers (Fenne 2005).

1.4 Development of body armour

As long as people have hurt each other, both parties of every single battle have had the wish to be inviolable so far. It led to many developments and a long chain of evolution through the various ages. In the development of armour to protect people against attacks, the vest is part of the body protection. Also, the materials which are used are

still under development. Ancient body armour should provide protection against violence through stabs, cuts and bullets. Since the knife is one of the oldest tools but also among the oldest weapons of man, the development of defence in form of armour began his early start. The first knife-like weapons were made of bone or stone, the handle usually consisted of horn, bone or wood. Since the realization of winning metal and processing it, the manufacturing of blades for knives for the everyday use and as a long version in the form of a sword began. For some time now blades are made from high-performance ceramics. The simple design of blades and handles is evident in particular for the user but also for others to show a high hazard potential due to unintentional and intentional injuries (BGI 2004).

1.4.1 History

The development of body armour began, when humans started to attack each other. There are three different types of armour. Textile soft armour which was made of leather and linen fabric or a combination of both was used in the past. Another material, which was used, is chain mail made of metal rings. Also rigid armour made of horn, metal or wood found its use (Fenne 2005). The first body armour, which was mentioned, was 2500 B.C., which was manufactured out of metal or leather lamellae. The Assyrians were the first, who had textile multilayer linen armour and lamellar armour. This body armour was nearly similar for the next thousand years. The Greek used flexible lamellar armour and later also mail designs between 1500 B.C: and 500 B.C. Chinese used some layers of rhinoceros skin and the Mongols used ox skin layers. The Celts used chain-mail body armour out of front and back plates in the 4th century B.C. and the Romans adapted it in the 2nd century B.C. But also textile armour was used. The Japanese manufactured fabrics out of silk and quilted linen was worn in northern India. Between the 2nd and 12th century body armour out of chain-mails was adopted from the Europeans. The chains varied in link sizes, but also lamellar and textile quilted armour was used. In Europe only body armour made out of animal skin was used before (Horsfall 2000). Between the 12th and 16th century medieval knights used plate armour, so it can be mentioned, that from the beginning of the 17th century there was a continuous development of body armour but within the dominating plate armour (Fenne 2005).

After the 17th century, with the development of firearms, most body armour wasn't effective any more. In the 1850s an Australian developed a suit of boiler-plate iron body armour, which was the first effective protection against firearms (Fenne 2005).

The events of the The Second World War and the Korean War were turning points in the development of protective clothing. The army and Air Force came up with a flak jacket made out of nylon fabric (King 2009). In the 1950s the ballistic nylon vest was improved and in the 1960s first high performance fibres entered the market for armouring persons of risk (Fenne 2005).

In the mid-sixties, DuPont took the development of fibres a step further, introducing para-aramid, which was sold under the name Kevlar®. This material is a liquid crystalline polymer solution with extraordinary strength and stiffness and is proven to be five times as strong as steel, what makes it possible, to produce light and safe vests. Another manufacturer of this type of fibres is Akzo Nobel, who launched the product Twaron®. Soon after the invention of Kevlar®, it was introduced to the National Institute of Justice and adapted into a program which provided lightweight armour. In the years 1975 and 1976, two new effective vests made of Kevlar entered the market. The model K-15 combined out of a steel plate with 15 layers of Kevlar® aramid (Armellino 1976) and the model Y, which was the first pure Kevlar® aramid (Ayoob 1983). The new type of fibre and thus the safety vest made out of this fibre became necessary for the everyday police life and were proper for saving lives.

Since then, many new developments have penetrated the market, offering a broad variety of ballistic options and stab resistant body armour. New materials are advertised as being thinner, lighter and more resistant than the initial Kevlar®, however these materials are offered at higher price points. Examples for these new substances are DSM's Dyneema®, Teijin Twaron's Twaron®, Toyobo's Zylon®, Honeywell's GoldFlex® and Spectra® and Pinnacle Armor's DragonSkin®.

1.5 Technology of the stab event

The stab and cut resistance include very different and varying applications, like presented in the previous chapter. This means that the mechanical stress, caused by sharp or pointed objects in the respective areas vary widely (Horsfall, Arnold 2010). The threat of a stab attack can be classified in two steps of mechanism. The pure

stabbing or punching means a penetration by a pointed item, but without cutting, like an ice peak, awl, nail or needle, where the stab instrument penetrates the fabric, using the tip and displaces the fibres to the sides and slips through the fabric. The slash or cut mechanism describes the penetration of the fabric, before it slices through the fibres and cuts the fabric (Egres Jr et al. 2004). A threat by a knife includes both mechanisms, like shown in Figure 1-1. The tip of the knife penetrates the fabric and displaces the fibres and slips through the yarns, while the sharp edge slices through the fabric and cuts the yarns. It is important to understand the principle of both mechanisms in order to understand the variety of materials, which are used in dependency to their properties for designing suitable protection garments. In the following chapter, the mechanism of stab and slash penetrations are further characterized. In addition, the influencing factors beside the penetration instrument are given and the interactions between them are analysed. The resultant threats for human bodies complete this analysis.

1.5.1 Basics of the penetration mechanisms

There is no general or unique process to describe the mechanism of a stab attack, while there are a huge variety of stab instruments and stab processes, which can be cutting, punching or the displacements of fibres. The degree of blade sharpness causes different damages onto the fibres (Aming, Chitaree 2010). In general, a stab instrument gives energy to the surrounding material during the penetration until it comes to a standstill. With regard to the development of stab resistant equipment it makes sense to analyse the individual procedures since each of them absorbs energy and prevents a further penetration of the textile layers to the human body. The goal is to reduce the total puncture energy in a short period of time in order to stop the acting subject as early as possible.

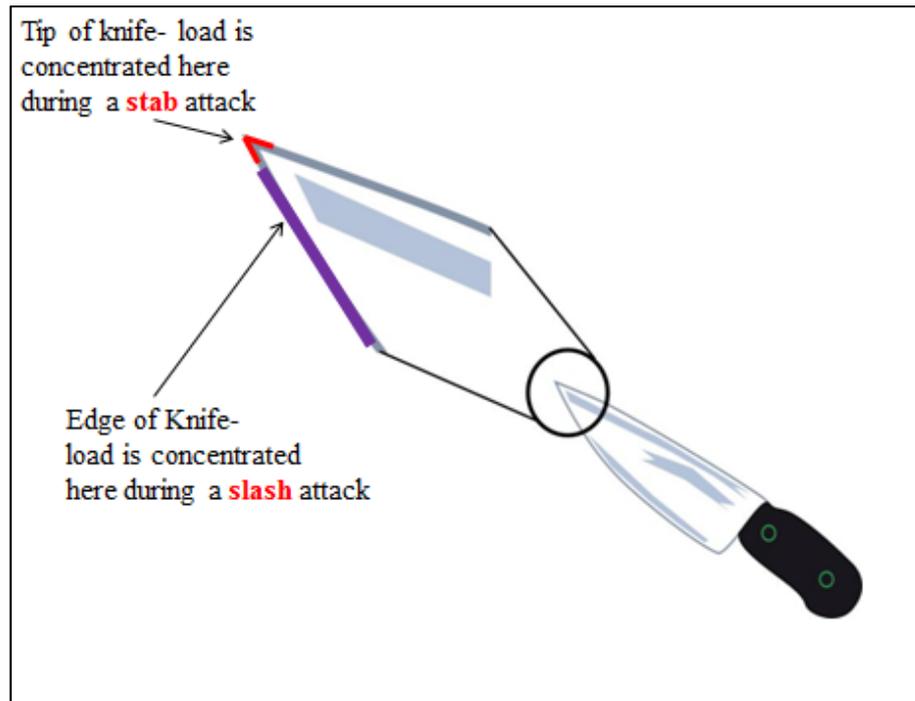


Figure 1-1: Edge and tip of a knife (Govarthanam et al. 2010)

During the impact of a knife, the directly affected fibres are displaced or destroyed. The energy on impact is derived in longitudinal and transverse directions, and is spread over the threads. Thereby the energy is weakened. The high strength of fibres in a fabric or a shield ensures that the energy is exhausted. Another part of the energy is transformed in deformation energy, which leads to the deformation of the overall structure; it results in a trauma and a stab wound. This energy absorption prevents a deep pointed injury. The cutting process is depending on the nature of the cut, the cutting tool and the movement characteristics. Due to the high contact forces, the blade will initially penetrate the fabric. The frictional forces can prevent a further opening through the penetration process so that each system, which increases the frictional forces acting on a blade, is adapted to reduce the penetration. Also surface damage to the knife, its blade and the tip minimize penetration into the other layers significantly. In order to dissipate the energy caused by the knife blade, a particularly hard material is required (Horsfall 2012).

Summarizing, the cutting process itself can be divided up into three processes after Feiler: (Feiler 1970)

1. The work or energy to overcome the molecular bonding forces. It depends on the material's specification.
2. The deformation work, which is the sum out of the elastic and plastic deformation, depending on the physical properties of the material and the displaced volume.
3. The frictional force, which depends on the material's properties, the surface structure of the cutting instrument and forces acting on the surface.

This theoretical approach is often different from the practice, because as shown on the one hand, in real life, a variety of instruments is used and secondly, a classification of the injury's energy is difficult, as it will be shown in the following chapter. Also the distinction between the two mechanisms of stab and cut injuries is difficult, because some instruments include both mechanisms, like shown. Therefore the mechanisms are summarized in the following chapters as one threat. Also a lot of influencing factors have to be taken into account.

1.5.2 Influencing factors

The cutting process is influenced by different parameters, which interact with each other. They can be split up in two areas, the technological factor, which includes the stabbing weapon itself with its geometry and the kinematic energy of action and the material factor of the cut material itself (Feiler 1970; Finkelmeyer 2002). Also the influence of human during a stab attack must be taken into account.

1.5.2.1 Technological factor

From the technological point of view, the threat level is influenced by the kinetic energy of the knife-arm-system, which depends on the instrument's factors like size and shape of the weapon and its blade, the diameter and the angle of attack (Finkelmeyer 2002; Yahya et al. 2014). Also the steel hardness, blade hardness and the knife grip influence the threat level (Scott 2005). Both cut energy and failure initiation strain decrease with a decreasing slice angle. The cut energy drops greatly when the blade angle decreases from 90° it falls from 50 to 75% at a blade angle of 82.5° and decreasing further, but more gradually, at lower angles. At a 45° blade angle, cut energies fall between 3 to

10% (Shin et al. 2003). The different kind of cutting methods can also vary. As a basis for testing procedures Heudorfer gave an overview about the different methods. These differ by the cutting tool, the characteristics of movements, like shown in Figure 1-2. The movement characteristics depend especially on the cutting angle, which is different for the types of cutting methods (Reumann 2000).

Description	Direction of impact force
Falling cut	
Cut through with put on round blade	
Cut through with put on blade	
Continue cut	
Tearing test	

Figure 1-2: Cutting test methods (Reumann 2000)

The “falling cut” and the “cut through with a put on blade” are similar to a stab attack. A typical tool for this mechanism is the cutter knife. The continue cut relates to a method, where an already damaged fabric is further cut with a sharp knife. The movement characteristics depend especially on the cutting angle, which is different for each type of cutting method. As a result, the test speed and thus the impact energy varies. To analyse the kinetic influencing factors, also the physical strength and emotional state of the assailant have to be considered (Govarthanam et al. 2010). The gender, fitness level, body size and experience of the assailant are also important factors (Scott 2005). The values, which are assumed for a stab impact, vary greatly between the countries, because of the different principle of experience which is used. In the United States and Germany maximum impact energy of 100 Joule is assumed, while in Great

Britain values of 42 Joule are supposed. Experiments in Switzerland brought mean values of 35 Joule (Damm 1997). Horsfall found out, that an overarm attack can reach up to 115 Joule and 64 Joule was reached by an underarm attack (Horsfall et al. 1999). In another research study, energy levels of 103 Joule were reached by volunteers (Chadwick et al. 1999). One study compared over- and underarm attacks with a long- and a short stabbing action. Long way attacks show higher speed values with up to 3.8 m/s for long overarm, 3.1 m/s for long underarm attacks, 2.8 m/s for short overarm attacks and 2.4 m/s for short underarm attacks. Longer ways cause higher speeds and result in higher impacts (Miller, Jones 1996).

1.5.2.2 Material structure factor

To produce soft body armour, it is necessary to manufacture textile structures out of the previous mentioned materials. Due to their construction, textile structures have the advantage to be flexible and can be woven, non-woven, knitted or laminated structures made of yarns or fibres and due to their construction they have different properties. The main goal of the fabric is to absorb energy in case of an impact and make sure that no perforation occurs. Therefore an inelastic structure is most favourable, because the fibre itself absorbs the energy and is not influenced by the construction, which gives way from the amount of yarn reserve and varies on the type of construction.

Stab or cut resistant fabrics should resist against impact as long as possible. The material, which is penetrated, influences the impact by its chemical and microscopic structure and therefore by its mechanical properties. Also the sample size, the thickness and the density are important influencing factors. A higher number of fabric layers absorb more energy and especially spacer fabrics absorb more energy than plied fabric layers (Cunniff 1992).

1.5.2.2.1 Stitching

The energy absorption can be increased by stitching of the fabric, because the fabric layers are closer together. The lower gap between the layers leads to better interactions between the fabrics. The distance between the seams have no significant influence (Ahmad et al. 2008). Also the movement of the fabrics will be controlled through the stitching, which leads to a better puncture behaviour (Suhaimi et al. 2012). Opposite to that, Bilisik found out, that unstitched and stitched fabrics absorb the same energy but stitching prevents deformations in one direction of the structures (Bilisik, Turhan 2009).

1.5.2.3 Influence on human by the threat

To classify the threat level, the energy of the threat has to be known, whereby the energy level, which can be reached, varies greatly. Sharp weapons cause wounds, which can be characterized by their depth and width in the skin. Most of the time the injury is a combination of stab and cut, because usually both the attacker and the victim are in motion (DiMaio, Dana 2006). A study in 1986 in Great Britain with 539 adult victims showed, that 20% of them were attacked by sharp weapons, from which 11% were broken drinking glasses and 6% were sharp knives. In total 54% of them were injured through laceration (Shepherd et al. 1990). A simulation of stab penetrations is difficult to do. Ankersen made stab tests on synthetic chamois and pigskin, which is similar to the human skin (Ankersen et al. 1999). The most dangerous influences on the injury level are the depth of the stab injuries and the body areas, which are penetrated. They are presented in the following.

1.5.2.3.1 Depth of stab injuries

The depth of the of stab injuries determines the extent of the injury additionally to the shape of the stabbing instrument and the fabric structure. The depth depends on the victim's body mass, his reaction and the position of the assailant, which means the angle of attack. The stabbing potential is also influenced by the assailant. Here the influencing factors are the gender, his fitness level and body mass, the physical size, mental state and the training experience (Scott 2005). Connor made computer tomographic measurements, carried out on 71 subjects to evaluate the distances of organs to the skin. The results show that with stab wounds at a depth of up to 9 mm no organs are injured because the smallest distance of an organ to the skin with 9 mm was measured to the liver. The spleen lies in a distance of 12 mm to the skin and the kidneys 19 mm. The pleura have a distance to skin of 10 mm and the pericardium 12 mm. There is no difference between male and female subjects (Connor et al. 1998). Bleetman comes to the same conclusion, (Bleetman, Dyer 2000) after which the Home Office Police Department has taken those parameters into account and has set a maximum allowable penetration depth of 7 mm in their standards (Croft, Longhurst 2007c).

1.5.2.3.2 *Body areas*

After Fenne (in Scott 2005, page 669) the thoracic and abdominal region suffers the largest share of attacks. The head, facial area and arms are the following two most likely attack surfaces. The fewest puncture wounds are recorded as the legs, the neck and the shoulder area.

Another study with police officers as victims in the year 2003 showed, that 42% were injured in the face, 6% to the trunk, 14% to the hands, 12% to the arms and 11% to the legs like presented in Figure (Horsfall et al. 2013).

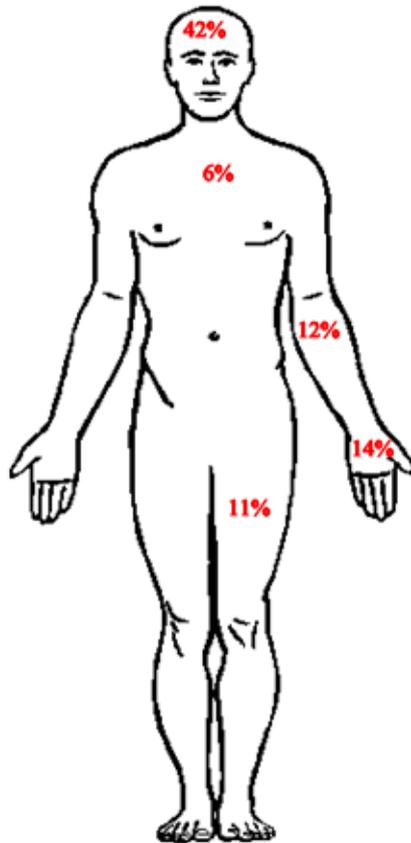


Figure 1-3: Areas of injuries after Horsfall (Horsfall 2000)

1.5.3 Conclusion

The stab mechanism is a complex and variable process. To design improved body armour, the physical properties of the material but also the mechanism during a stab attack has to be recognized. Only if the interdependencies are taken into account, better panels can be developed for a higher protection level.

From the multitude of factors it is difficult to define a level of protection. This is also reflected in the large number of standards, which will be discussed later. Also high kinetic energies are not always critical. A needle bends for example during a fast penetration while it perforates the fabric at a slow penetration level.

An attack can only be inhibited, but an injury cannot be completely prevented. The goal is always to absorb as much energy as possible, so that the penetration of the weapon is thus reduced and the risk of injury decreases. Due to the high variation in blades, mechanism, sharpness and geometry of the blade and many other factors, like presented before, it is difficult to characterize the threat level of impact and define a test method which covers the variety of stab mechanisms and other relevant factors. That is one reason, why any comprehensive solution is currently not available.

1.6 Body armour technology

1.6.1 Composition and construction of body armour

Every stab resistant vest consists of three main parts, which are in most cases, manufactured from completely different materials, chosen due to their specific properties, ensuring, that the final product offers the best possible safety to its wearer. The simplest construction of a vest is a panel out of two layers which build the carrier. In these layers the stab resistant package panel then can be inserted. The carrier is the only part of an impact resistant vest that actually allows any design alterations, which makes it most valuable for organizations like Police Forces or Armies, since it provides space for additional equipment and any other specifics that reflects the profession of its wearer. There are two basic options available for the carrier: a carrier with removable stab resistant packets and / or a carrier in which the panel is permanently inserted. Minds argue about the pros and cons of both options, but in the context of female body armour it should be mentioned, that removable plates allow the wearer and bearer of such a vest a major reduction of weight when several plates are not necessarily needed.

Further design options are also closely related to the functionality of the vest and the field of employment of the wearer (Moureaux et al. 1999). The carrier and its mode of functioning are mostly independent of the style of the stab resistant panel and manufactured for hard or soft body armour.

The stab resistant package panel part is the most important one of any type of body armour, because it is designed and destined to stop the impact and save its owner. It has to fulfil many requirements and testing standards such as a superior tensile strength (for soft body armour only), specific weight requirements, and the ability to distribute the energy that needs to be absorbed to the highest possible amount of available space and, lastly, a very low value in terms of elongation during breaking load. They have to fulfil their protection level also after ten years of use (Gäbler et al. 2011). These standards and requirements apply to soft as well as hard body armour panels. But apart from these common goals, the two types of ballistic panels differ greatly from each other. The first type of body armour to be regarded in this thesis is the hard body armour.

1.6.1.1 Hard body armour

The hard ballistic panel is, opposed to the soft ballistic panel, made out of some sort of rigid material, including ceramic tiles, metal plates and silicone carbide or boron carbide plates (Hani et al. 2012). From a historical point of view, this working principle made up the very first types of body armour. In history, steel was the only preferably used material that could perform well under the given stress of a mechanical impact. However, nowadays, a producer of body armour garments can also choose from oxide ceramics, polyethylene and boron carbide or silicone carbide ceramic, mostly fusing several materials with specific properties together into one hard ballistic package, which has a very specific wavy form (Horsfall 2000). Plate armour is the simplest manufactured body armour and gives a high level of protection. It consists of rigid plates in different sizes. The disadvantage lies in the missing flexibility and thus a bad comfort. Also because of the kind of manufacturing, the openings at the neck and armholes have to be large enough to give a certain level of freedom to the movement. In 1987 Fritch registered a patent out of multiple panels with front and back body armour inserts to be worn under regular clothing. Each panel consists of a ply of titanium metal bonded to a ply of aramid fibre woven cloth. The panels are arranged overlapping (Fritch 1987). Another innovation is scaled armour out of small rigid plates, which are much more flexible (Beck 2006; Sacks, Jones 1996). But in case of an angled attack it

gives a very poor protection, because the knife can slip between the plates. To give a better comfort, some researchers combined the plates with cut resistant yarns, which are wrapped around the plates. This gives a better breathability to the wearer (Harpell et al. 1993). Another used material is granular ceramic armour, which consists of an array of small ceramic elements which is bonded together on a rigid backing (McLean, Frutiger, S. Dabek, R. Reeves, J. 2010). This is mostly done to create a higher degree of adaption to the body for the vest as well as to better handle the energy that needs to be adsorbed when an impact hits the garment. In theory, hard ballistic packages are sufficient to stop any kinds of impacts; nevertheless, they are mostly used in a combination with soft body armour panels to maximize comfort and safety for the wearer of the vest. The working principle for hard ballistic packages underlies one simple principle: the panel should be harder than the impacting threat. Depending on the materials used for panel and weapon, both can deform during the impact due to the high energies and forces working against each other at this point. Furthermore, energy can be led away from the wearer if impact fragments rebound in the opposite direction. With steel, the molecular structure at the hitting point can be destroyed during the shock, causing the performance of the vest to decrease dramatically.

1.6.1.2 Soft body armour

Soft body armour is part of the PPE, most times in form of a vest, which protects the body against impacts, like ballistic impacts or other impacting objects like knives or spikes.

In the construction of soft body armour, several layers of textiles are put together to a system against impact threats. The panel should maintain the freedom of movement while still covering the most important areas, which are the organs of the body. That is why they are designed in an ergonomically cut with consideration to the human anatomy. The panel also needs to provide protection against light and humidity, because some stab performance materials are sensitive to these influences and can lose their properties. Therefore they are sealed into a waterproof and impermeable light plastic foil and further encased into a textile carrier. This prevents the effect of light and moisture to the fabric and therefore reduces the loss of performance.

A soft body armour panel consists of high performance fibres or filaments that are fused in a woven or other bonded layering. Flexible body armour is also made out of multi-

layered fibre material or a blend of cut resistant fibres with a metal core (Kolmes, Pritchard, C.E. Mussinelli, M. 2007; Donovan 1984; Zhu, Prickett 2003).

In general, the application of soft ballistic packages is limited to prevent knives to penetrate, however, with the right amount of layering and a proper high performance fibres as a base, the soft ballistic panel can be improved, to prevent threads entering the human body tissue.

Apart from the general valid and needed properties of the fibre type, the type of weaving or bonding that fuses the fibres together is of highest importance to the functioning of the finished garment, as described before (Cavallaro 2011).

In principle, two different fabric constructions are used for manufacturing soft body armour. On the one hand are conventional fabrics and on the other hand are unidirectional laminate nonwovens (UD), which are also called shields.

1.6.1.2.1 Woven Fabrics

In the field of soft body armour construction, woven structures are very common among other fabric constructions. Up to a certain velocity and density, square woven fabrics can be more resistant than equivalent hard body armour (Shepherd et al. 1990). The pattern that is used the most is square woven plain or basket weaves, like presented in following.

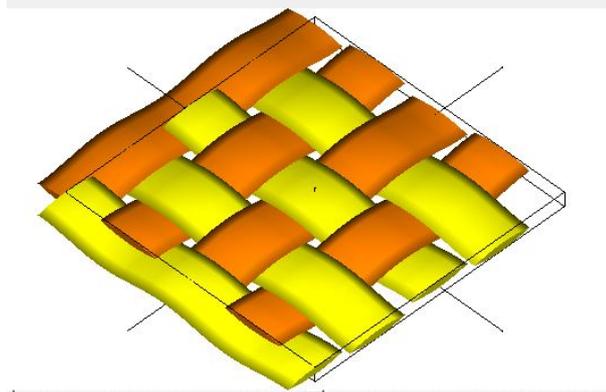


Figure 1-4: Square plain weave

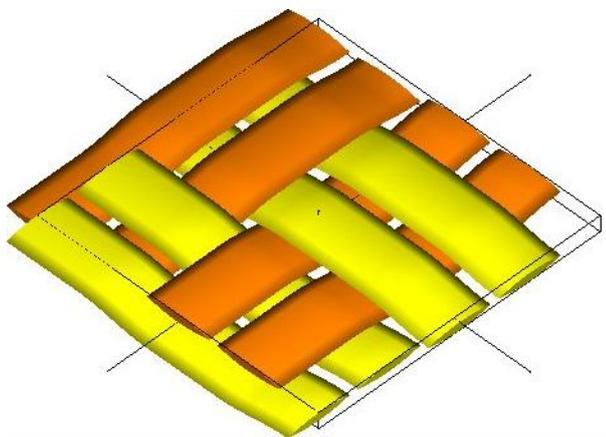


Figure 1-5: Basket weave

A balanced weave is normally used for the construction of protection garments, because unbalanced weave structures lead to an asymmetric transverse deflection (Cunniff 1992). In this context, the cover factor of the fabric is from high importance. Studies have shown that cover factors between 0.6 and 0.95 give an optimal performance (Scott 2005, p. 537). Values below are too loose and such loose yarn structures lead to a displacement of the yarns, which then lead to a penetration of the fabric (Cheeseman, Bogetti 2003). Values above 0.95 result in a degradation of the yarns under tension during the weaving process. Also the crimp of the inserted yarns increases with a higher density, which is not desirable; because the energy dissipation mechanism is depending on the crimp of the fabric, which has to extend first until the main mechanism can take its effect on the energy absorption (Bilisik, Korkmaz 2011). But a high yarn pre-tension can reduce the cut resistance (Shin et al. 2006).

1.6.1.2.2 Laminates

Laminates are a combination of two or more materials to combine the useful properties of the individual components. These laminates are called Unidirectional laminate fabrics (UD-fabrics). They are nonwoven matrix systems, where yarns are aligned unidirectional in one layer and the following layer is aligned in another direction, normally 90° to the first one. They are permanently bonded together by heat, pressure or adhesives. The properties of these UD-fabrics depend on the type of fibre, the type and amount of resin, the number of layers and the bond between resin and fabric (Bhatnagar 2006). Different structures are used for stab resistant PPE and are discussed in the following sub-sections.

1.6.1.2.2.1 Spectra Gold Flex®

One of these structures or shields is the trademark Spectra Gold Flex® by Honeywell, which is made out of four layers aligned aramid fibres fixed with resin (Park 1999). The produced vests out of this material are thin and resultant of this light and flexible.

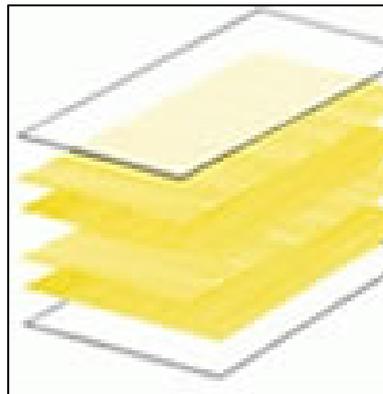


Figure 1-6: Spectra Gold Flex Shield® (Honeywell 2006)

1.6.1.2.2 Dyneema UD

Dyneema UD is a unidirectional laminate made of two layers of polyethylene filaments cross plied and sandwiched in a thermoplastic film. The construction is presented in Figure 1-8. It is one of the strongest laminates for protection.



Figure 1-7: Dyneema UD (DSM 2012)

The advantage of the shields is that it has no crimp issues, due to the different processing techniques and lighter weight. Apart from that also brittle materials like glass or carbon can be inserted. A disadvantage of these constructions is that there are no linkages between the yarns. They are just connected by the resin, which is not as strong as the mechanical linkage of woven fabrics.

1.6.1.2.3 Improvements of woven fabrics

Furthermore, the manufacturer might want to add special coatings to his product to support functions, especially when working with para-aramids, a hydrophobic finish to ensure that the life-saving capillary system existing between the single filaments of the impact resistance package cannot fill with water and thus fail the wearer when it does not take up the lethal energy properly in the very moment a knife penetrates the vest. This effect can be achieved through the usage of a resin-like coating that soaks the filaments, which not only provides water-repellence but unfortunately simultaneously makes the weave heavier and harder (Jenkins, Ren 2000; Breukers 2003). The simple equation every company producing and designing soft body armour needs to face is: the better the waterproofness, the harder and less flexible the fabric. Also a polymer film between the layers prevents the slippage and fixes the yarns (Fuchs et al. 2003).

Another way to improve the performance of such a panel is to add a liquid, called Shear Thickening Fluid. The Shear Thickening Fluid, short STF, as the name already indicates, behaves like a solid when encountering mechanical stress or shear. STF is a colloid, which is highly filled with miniscule, rigid and colloidal particles that repel each other slightly and are suspended in a liquid. Due to the fact, that the particles repel each other, they can easily float through the liquid without clumping together or forming a layer at the bottom.

With the energy of a sudden impact, hydrodynamic forces overwhelm the repulsive forces that exist between the tiny particles, driving them to stick together and forming hydro clusters.

As soon as this energy is taken away, the particles start repelling each other again, causing the hydro clusters to fall apart and the STF to be liquid once again.

The production of STF is fairly simple: it is made of colloidal silica particles, a component, only a few nanometres (~450nm) in diameter of sand and quartz, suspended in polyethylene glycol, which is a polymer commonly used in e.g. lubricants. Due to the size of the particles, some reports describe this fluid as nanotechnology. The STF acts like a liquid, providing high flexibility and no restriction to movement, until an object, in this case a blade, strikes it forcefully. At this point the relative motion of the high performance yarns or fibres deform the fluid within milliseconds, forcing a transition into a rigid state, providing less flexibility but high protection. Studies show, that the addition of STF improves the stab behaviour of fabrics (Li 2012).

1.6.1.3 Conclusion

Multi-layer fabric packages of aramid, which are used for mechanical impact protection, often don't offer the required protection against stab protection with a sharp pointed weapon. While developments of fabrics are already found, that enable adequate stab resistance, there is still a large part of the solutions where combinations of different structures of textiles with metals are used (Scott 2005). Also materials with the required mechanical properties like strength or shear in form of plates or metal rings are used. Stainless steel and titanium plates are also applied for this application. Ceramic plates are also an ideal material, typically made of aluminium or boron carbide (Scott 2005). A combination of textile materials such as aramid with steel or ceramic in form of composite structures or sandwich constructions can give improved stab resistant results, while they are lightweight and flexible. Also cut resistance gloves give a better

protection using a combination of cut-resistant fibre materials such as para-aramid with steel wire. Also gloves out of leather with a high material thickness are established as an important cut-resistant material (Heudorfer et al. 1996). Pure textile solutions often still do not offer the required protection. Therefore it is important to analyse those influential factors that cause the decreased stab resistance and develop improvements for better panels (Karahan 2008).

1.6.2 Materials

In the manufacturing of textiles for protection against mechanical risks, like stab- or slash resistant materials, different materials are used. The main task of these materials is, to absorb and dissipate the energy, which is transmitted by the stab instrument. As a result of this, the different kind of stab instruments can be stopped or not (Damm 1997). The current development of stab resistant equipment often consists of one textile layer in combination with an additional layer, which has the task, to increase the stab resistance. In the following materials are presented, which are common used as personal protective equipment against mechanical risks, because of their high breaking strength and high modulus properties to be able to absorb a high amount of energy (Fenne 2005).

The most common fibres that are used for body armour products are Kevlar®, Spectra®, Dyneema® and Zylon®. These fibres provide excellent tenacity properties and a high modulus. The most important properties are summarised in Table 1-1. All the fibres listed provide excellent strength-to-weight (tenacity) property and a high modulus.

Table 1-1: Comparison of fibre properties (Hearle, J. W. S 2001)

	Tenacity	Modulus	Breaking Extension	Density	Moisture Regain
	N/tex	N/tex	%	g/cm ³	%
UHMWPE (Dyneema/ Spectra)	2.5 - 3.7	75 - 120	2.9 - 3.8	0.97	0
ARAMID (Kevlar/ Twaron)	1.7 - 2.3	50 - 115	1.5 - 4.5	1.54	5
PBO (Zylon)	3.8 - 4.8	180	1.5 - 3.7	1.44	0

But not just the high tech fibres have to be taken into account, also other fibre types show an important role in this field.

Studies of the properties of wool have shown that the rough surface of wool, caused by the scales, have very high friction forces (Bahadir, Jevsnik 2014; Frishman et al. 1948; Lindberg, Gralén 1948; Mercer 1945; Zurek, Frydrych 1993).

During the stab test the yarns slide apart when the blade penetrates the fabric. Therefore Sinnppoo (Sinnppoo et al. 2010) describes the use of wool fabrics in his studies. He put mid-micron wool fibres into the woven structure to restrict the separation of the aramid yarns and therefore also the friction behaviour of the fabrics. The function of the wool is not to replace the aramid as the stab resistant material. As the friction is most important in the area, where the knife penetrates the aramid fabric, the function of the wool layer is to decrease the lateral separation of the yarns of the outer fabric layer.

The expected effect of decreasing the friction between the yarns is established in the special surface of wool. The scales effect like barbed hooks, which claw into the surface of the nearest yarn and avoid the sliding of them. The wool yarns prevent that the filaments slide apart, they hold the directly impacted yarns in place for a better dissipation of the impact energy. The scales stuck into each other or into other surface irregularities. (Simpson, Crawshaw 2002) Because of the longitudinal friction between the yarns of the wool and the filaments of the para-aramid the pull-out behaviour will decrease (Sinnppoo et al. 2010).

In the following, the fibre properties are explained in detail.

1.6.2.1 Para-Aramid

The most common material for protective vests is para-aramid, because it can be found in the most commonly manufactured products (Fenne 2005). For the first time, the yellow organic synthetic fibres appeared in 1965 under the brand name Kevlar® from DuPont. The other well-known brand is Twaron®, produced from Teijin Aramid and is basically the same material as Kevlar®. Para-aramid is an aromatic polyamide, consisting of cyclic aromatic elements and the amide group, namely phenyl group, which is responsible for the high performance properties, like shown in Figure 1-9. Not just these groups, but also the linear structure of the polymer chains are responsible for these properties, because they can form easily strong intermolecular bonds.

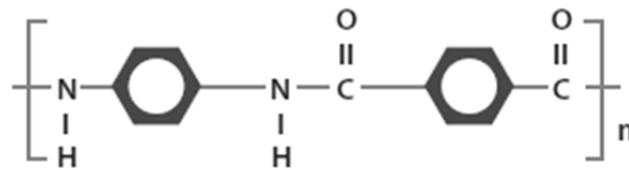


Figure 1-8: Chemical formula of aramid (Teijin Aramid 2012)

Para-aramid has very good strength-to-weight properties, like high strength, high modulus, high dimensional stability and hence an excellent cut resistance, which is a result of the crystalline structure with the molecular chains oriented along the fibre axis (Teijin Aramid 2012).

The main problem of the para-aramid fibres is the susceptibility to hydrolysis and sensitivity to light, why it has to be protected from light and moisture. The low resistance to UV radiation can cause the fibre to lose up to 75% of its strength. Therefore the material is wrapped by an opaque and impermeable cover to prevent any kind of degradation and loss of performance (Horrocks, Anand 2000).

1.6.2.2 Ultra-high molecular weight Polyethylene (UHMWPE)

UHMWPE is a special produced polyethylene with extremely long chains of polyethylene, which are all aligned in one direction. The fibre production is carried out by solvent or gel spinning and allows the molecules already to align in the solution, which leads to extremely long molecular chains. The additional drawing process makes the molecules become even more orientated.

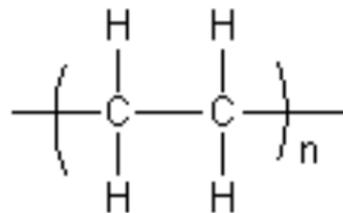


Figure 1-9: Formula of Polyethylene

Under the current used fibre types for protection against mechanical threats, it is the lightest material and the best material referring to its strength to weight ratio. It is stronger than steel but also stronger than aramid and is not prone to degradation. The low melting point of 150°C restricts its use to low temperature applications (Horrocks,

Anand 2000). The most known trademarks for UHMWPE products are Dyneema® from DSM and Spectra® from Honeywell.

1.6.2.3 Poly-para-phenylene-2,6-benzo-bisoxazole (PBO)

PBO has very good mechanical properties, caused by the benzene ring structure and the rigid rod-like chain molecules. The module of elasticity of PBO is much higher than the one of para aramids. The famous known trademark of PBO is Zylon® from Toyobo (Toyobo Co. 2005). Since the failure of a Zylon® body armour vest, the assumption of degradation was taken into account. Due to the protective performance loss a few years after the production of a vest made of Zylon® as well as the loss of performance through moistening of the substance, Zylon® based body armour cannot provide the intended level of protection. As there is no visible indication of aging, PBO vests are not used anymore (Polizeitechnisches Institut (PTI) 2001).

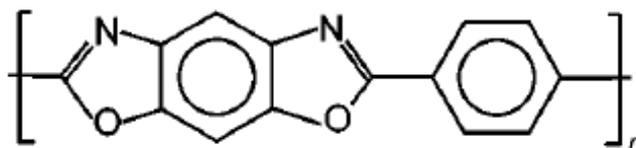


Figure 1-10: Formula of PBO (Hearle, J. W. S 2001)

1.6.2.4 Wool

In the following, the wool characteristics related to the stab resistance is presented in detail. Wool can absorb between 14-18 % of moisture in standard atmosphere. This is an important fact due to the increase in moisture on the aramid yarns, which leads to a higher yarn slippage. Furthermore the comfort of a panel made of blend of wool and aramid increases because of the water vapour absorption (Mahbub et al. 2014). The friction is available at two stages – one is fibre to fibre friction inside of the yarns, which influences the compressibility of the yarns and thus as well the forces, which act to the neighbour yarns during penetration. Another stage is at the yarn level – the fibres on the yarn surface contact with the fibres of the other wool and aramid yarns and causes again a higher friction. Furthermore, the hairiness of the wool yarns influences the friction between the wool yarns and the aramid yarns. It can be assumed, that in general at every level single fibre surfaces connect to another one, independent if it is on fibre or yarn level. The second important characteristic of wool is the friction

behaviour, which can vary significantly depending on several parameters. Because of the random orientations of the scales of fibres in a yarn, the coefficient of friction μ depends on the surface, direction of scales (with/against scales), the kind of wool, e.g. fine or coarse, and the surrounding conditions like temperature and air humidity (Frishman et al. 1948; Mercer 1945). Another influence is caused by the different contact points of the scales parts and angles (Mahbub et al. 2014). The structured surface of a wool fabric has a higher friction coefficient in comparison to the smooth surface of an aramid fabric, due to the imbricate structure (Zurek, Frydrych 1993). Some exemplary friction values μ of wool are between 0.11 and 0.13 in direction with scales, between 0.15 and 0.21 for the same fibre direction and between 0.38 and 0.61 against scales (Simpson, Crawshaw 2002). The values are differentiated between static and kinetic values.

The mean frictional coefficient against scales is higher than with the scales, (Frishman et al. 1948; Lindberg 1953) but a microscopic analysis of a typical wool yarn shows, that the fibres lay uniformly distributed in both directions, like the example in Figure 1-11.

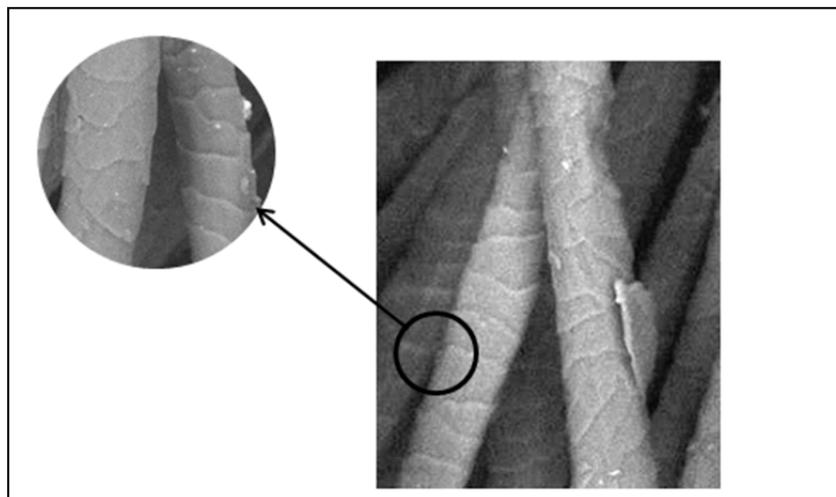


Figure 1-11: Direction of fibres in a wool yarn

Therefore it is assumed, that the mean frictional force of a yarn and also of a fabric is an average of the frictional force of both directions, with and against scales. Ajayi (Ajayi, Elder 1997) tested several different fabrics with a wide range of physical properties to show all these influences on the friction coefficient. He also found out, that the friction

is also affected by experimental conditions, like changes in the normal pressure and a limited influence to the test velocity.

1.6.3 Yarns

Not just the right material has to be chosen, but also the yarn has to fulfil requirements, because they are the basis of the structure, which is manufactured for the protective garment. One of the most important properties is the linear density. In the production it is easier and cheaper to produce coarser yarns with more filaments and also the handling is easier. But nevertheless, yarns with a lower linear density are lighter and show a better performance against mechanical impacts due to higher energy absorption because the bundle effect is lower. Bundles lead to a poor contact area between the impact instrument and the filaments. Furthermore yarns made out of aramid filaments, which are really fine and can consist of 1000 monofilaments, give the filaments the opportunity to move individually and can spread while being impacted (Eichhorn 2009). To give the filaments the opportunity to move individually, also yarn twists as low as possible are recommended.

1.6.4 Physical properties of textile body armour

According to the German technical guideline TR, a body armour vest has to fulfil the following requirements: a vest has to tighten easily and should not restrict its wearer in his movements. It should also be able to be adapted within a standard size to the body size (Polizeitechnisches Institut (PTI) 2008).

In general, body armour vests cover only the chest and back area of a human body. Thereby the risk of serious or fatal injuries is minimized. Depending on the protection level, the wearer requires light and flexible protection equipment. However, there is a direct inverse relationship between protection and flexibility (Horsfall, Arnold 2010). Thus, the requirements of comfort from the perspective of the wearer and the request to the protective performance stand opposite to each other (Fenne 2005). Because of the required protection level, body armour vests are made out of several flexible layers, which can consist of up to forty layers and can lead to inflexibility and heaviness. This can cause a vest to interfere with the movements of its wearer. A research study showed that it is only possible to stop a knife with an amount of minimum 35 layers (Barnat, Sokołowski 2014). An average multilayer body armour panel can consist of forty to fifty layers, which has a negative impact on the mobility of the wearer (Fenne 2005). A

lot of researchers worked on new technologies to reduce the weight of such a panel, while improving the comfort of it (Barker, Black 2009; Flambard 2000; Horsfall et al. 2013).

Studies of the German police have shown that especially in police interventions an insufficient acceptance is given. That means that many police officers don't wear their vests and are therefore not protected in dangerous situations (Polizeitechnisches Institut (PTI) 2001). Another study in this context analysed, that only 25% of these police officers wear their vests always during their work time whereas more than 50% never or seldom wear them (Lorei 2001). One reason is that they are exposed to extreme physical stress. Therefore they need fast reactions and they have to adapt to the body. Due to the long wearing times, protection vests should be comfortable and should not restrict the wearers in their movements.

The comfort of protective panels is determined by different influencing factors in dependency of the protection level, which is the most important factor, also for the wearer.

1.6.4.1 Psychological influences

Body armour vests have to fulfil the required protection level to let the wearer feel save. Thereby the wearer is motivated to wear it (Moser 2007). A vest should also be invisible under the clothing, because in case of an attack other body areas like the head would be the objective if an assailant notices the vest.

1.6.4.2 Thermo-physiological influences

The thermo-physiological comfort deals with the way clothing buffers and dissipates metabolic heat and moisture, so the heat- moisture exchange has to be ensured (Yoo 2005). Even during long times of wearing and high body stress, wearing of a protection vest must not result in a heat build-up. Body armour panels do not allow air circulations, but the sweat production increases by physical activities or high ambient temperatures. The problem is that sweat cannot evaporate on the skin. Wellbeing and performance of the wearer decline. That is one reason, why wearers feel uncomfortable when wearing vests (Lehmacher et al. 2007). Therefore, the moisture transport in fabrics plays an extremely important role in the clothing comfort (Yueping Guo et al. 2008). One way,

to get the present problem under control is the use of mesh fabrics as an inner layer of the clothing. These fabrics carry the moisture away from the inside to the outside.

1.6.4.3 Ergonomical influences

The fit is one of the most important properties for the user and should match the wearer's body. If the vest does not fit, lightness and softness play no role. It is still perceived as uncomfortable. The fit can be presented in four grading.

The first and easiest grade is a standard size. In the second stage, five grades of different lengths are included. The third grading includes contour variations in the armholes and necklines. An additional description of contours by mathematical curves is given in the fourth grade. That means an individual adaption to the wearer, considering the individual body characteristics such as cups for women and also an adaption to the kind of activity, such as long car or motorbike drives (De 2015).

Additionally to the fit, the weight of the vest is an important ergonomic factor. After long wearing times, the weight has a negative effect on the wearer.

Limits in flexible body armour panels out of fibrous materials are the high weight and inflexibility while a puncture is still possible. The main goal in the development of body armour is to increase the wearer's comfort, where particularly the flexibility is still a main factor. But these requirements of improvements are a challenge, because the protection factor cannot be worsened. Therefore a balance between comfort and protection has to be found (Scott 2005).

1.7 Protection levels and classification of body armour

Since there are many different levels of threats, there is no single vest that can protect the wearer against all kind of threats. Different constructions of soft body armour create different levels of protection and each has its own field of application. The usage of each construction of soft body armour is restricted to certain threats, respectively kind of blades, impact forces and speeds. The use of most constructions of textiles are not sufficient for protection, thus soft body armour cannot give enough protection against a penetration through sharp pointed weapons like knives or ice picks (Bhatnagar 2006). That is why it is necessary to classify the different types of body armour.

1.7.1 Technical guideline of the German police (TR)

The Technical guideline (TR) Ballistic body armour of police forces of the Federal Government describes the demands on protective vests of different protection classes (Polizeitechnisches Institut (PTI) 2008). A vest is designed to protect the wearer against projectile impacts or other mechanical impacts like attacks with knives. The freedom of movement of the wearer's body armour may be only slightly restricted. The scope is generally limited to the upper part of the body. Neither humidity nor temperature or other external influences may influence the protective effect. The protection of vests against impacts is specified with the protection class (SK for German: Schutzklassen). The classification is subdivided in five classes with different properties. In Germany, there is no safety class system that deals with stab-resistant vests only a system built up on the one already introduced, with the addition of “ST” in the nomenclature, which stands for “Stichschutz”, meaning stab-resistance.

The following table shall provide a profound overview of the different SK as well as their specific requirements:

Table 1-2: Protection levels TR (Polizeitechnisches Institut (PTI) 2008)

Protection level (SK)	REQUIREMENTS stab impact
SK L ST	Stab retardant against attacks with knives (blades)
SK 1 ST	Stab retardant against attacks with knives (blades)
SK 2 ST	Largely stab retardant against attacks with knives (blade) and pointed objects (e.g. needles and cannulas)
SK 3 ST	Largely stab retardant against attacks with knives (blade) and pointed objects (e.g. needles and cannulas)
SK 4 ST	Largely stab retardant against attacks with knives (blade) and pointed objects (e.g. needles and cannulas)

Combinations of bullet resistant specimen with integrated puncture protection have to be tested according to the guideline VPAM- KDIW 2004 class K1 and bulletproof test specimen with upgraded puncture resistance should be tested according to VPAM-BSW 2006 (Test Standard VPAM KDIW 2004; Test Standard VPAM BSW 2006). Stab resistant panels, which are conform to the TR, should resist according to test class K1 of

the guideline VPAM- KDIW 2004, which means, that body armour vests are allowed to be penetrated with maximum 20 mm at an energy level of 25 Joule.

1.7.2 The NIJ Armour classification system

In the most important standard of stab protection of the USA, the NIJ (National Institute of Justice 2000) for stab resistance of personal body armour, two protection classes are described. The protection classes distinguish between two different risk types caused by different type of threat instruments. The first protection class, the "Edged Blade class", protects against blades or knives, which are of high quality. Weapons of this quality are expected on streets. In this classification, the knife is allowed to penetrate a maximum of 7 mm. The "Spike class", however, offers protection against weapons, which are of less qualitative or improvised weapons, as they are used in prisons for example. They are allowed to penetrate a maximum of 20 mm. Within each protection class, the panel is further classified into one of three protection levels, which are depending on the stab energy the threat is expecting. Level 1 armour is a low-level protection armour, which is suitable for an extended wear and is generally covert. Level 2 armour is a general duty garment suitable for an extended wear and can be worn either overt or covert. Level 3 is a high level protection armour suitable to wear in high risk situations. It is usually overt. Table 1-3 gives an overview on the protection levels for the two protection classes:

Table 1-3: Stab protection classes NIJ (National Institute of Justice 2000)

	Protection Class E1 with a maximum penetration of 7 mm	Protection Class E2 with a max. penetration of 20 mm
Protection Level	Strike Energy in Joule	Overtest Strike Energy in Joule
1	24 ± 0.50	36 ± 0.60
2	33 ± 0.60	50 ± 0.70
3	43 ± 0.60	65 ± 0.80

The protective garment of the level 1 provides the lowest protection. It is mainly used as additional equipment and against low energy attacks up to 24 Joules. Body armour of level 2 is required for all policemen and can fend attacks with energy levels up to 33 Joules. Level 3 protective equipment is used in risky supported operations, and thus

forms the highest level of security with a protection against attacks of 43 Joules (National Institute of Justice 2000).

1.7.3 The UK Standard HOSDB

According to the HOSDB (Home Office Scientific Development Branch Body Armour Standards) for UK Police Part 1: General Requirements (Croft, Longhurst 2007a), protective clothing should protect in case of attacks with knives with edged weapons or spikes with edged weapons plus blurred weapons against injuries. The protective clothing is according to its protective function marked and divided in protection types. Equipment, which is marked as stab resistant, provides protection against sharp weapons and possibly in addition also against blurred weapons, like nails.

Protective garments which protect against bullets and knives are defined as “dual-purpose”. In relation to protection against knives and spikes HOSDB Body Armour Standards for UK Police Part 3: Knife and Spike resistance classifies three levels. KR1 and KR1+SP1 are the lowest level of protection, which is tested with energy values of 24 Joules. Protective clothing of this level is worn in cars or situations in less risky environments. The average protection level corresponds to KR2 and KRS+SP2, tested with energy of 33 Joules. This protection level is required for policemen to be worn daily. Protective clothing of the highest levels KR 3 and KR3+SP3 are only briefly worn in very risky situations and are tested with an energy level of 43 Joule.

Table 1-4: Protection levels HOSDB (Croft, Longhurst 2007b)

Protection Levels	Energy Level E1 (Joules)	Maximum penetration at E1 (mm)	Energy Level E2 (Joules)	Maximum penetration at E2(mm)
KR1	24	7	36	20*
KR1+SP1	24	KR1=7, SP1 =0*	KR1=36, SP1 = N/A	KR1=20*, SP1 = N/A
KR2	33	7	50	20*
KR2+SP2	33	KR2=7, SP2 =0*	KR2=50, SP2 = N/A	KR2=20*, SP2 = N/A
KR3	43	7	65	20*

KR3+SP3	43	KR3=7, SP3 =0*	KR3=65, SP3 = N/A	KR3=20*, SP3 = N/A
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The penetration must not exceed 30mm to be permitted at E2 knife testing and one penetration (no depth limit) is permissible for spike testing (Croft, Longhurst 2007c).

1.8 Testing methods, test standards

Like explained before, the stab event includes the stab and the cut or slash action. Due to this, the known test standards for stab and cut methods of textiles are explained as followed. The method for stab testing will be explained later during its application in testing.

1.8.1 Stab methods

The stab resistance of stab resistant textiles can be tested according to different test standards. In Germany or other German-speaking countries, the VPAM test instruction VPAM KDIW 2004 “Stab and impact protection” is widely used.

The principle of measurement is shown in Figure 1-12: a blade of a defined sharpness and size drops from a defined height which depends on the energy level for the stabbing impact. The penetrated fabric layers are positioned on plasticine, a modelling material that on the one hand absorbs the penetration of the knife and on the other hand gives the opportunity to measure the different depths of penetration. The knife is mounted on a sample holder and the drop mass of this unit is 2.5 kg. To ensure that the knife can fall on the sample in such a way that the tool strikes it at a 90° angle, the sample holder is led by rails. As samples of different thicknesses are tested, the drop height is adjusted depending on application, to determine differences between the samples. Afterwards, the stab depth in the plasticine is measured by using a ruler.

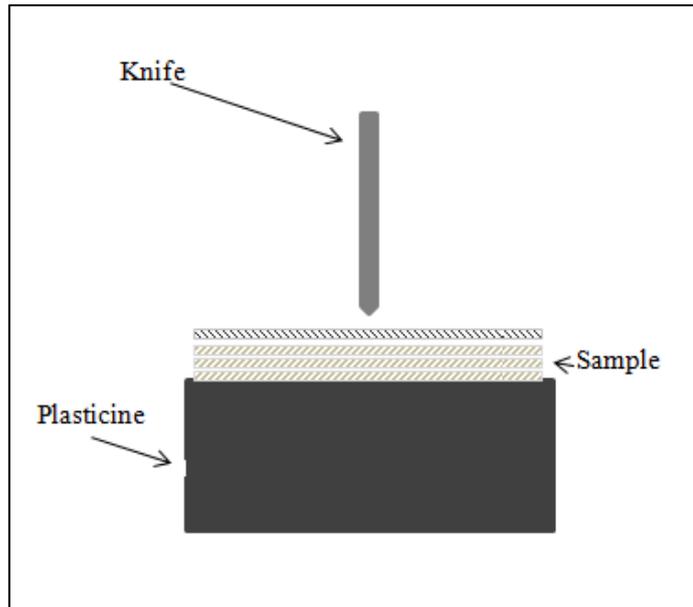


Figure 1-12: Test equipment stab resistance

According to the standard VPAM KDIW 2004, the fall height should be set, that a potential energy of 15 Joule has to be ensured to reach results of a stab depth lower than 10 mm or 25 Joule for a maximum stab depth of lower than 20 mm.

With the assumption, that the knife falls down without creating frictional forces at the rails, the falling height can be calculated by

$$W_{POT} = m * g * h \quad (1)$$

Where W_{POT} is the potential energy, m is the mass of the knife with the holder in kg, g is the gravity and h is the falling height. The weight by the knife plus holder is given by 2.5 kg and the defaulted potential energy is 15 Joule or 25 Joule. Due to this, the adjustment of the fall height has to be calculated as follows:

$$h = \frac{W_{POT}}{m * g} \quad (2)$$

The outcome of this is a height of 0.61 m for 15 Joule potential energy and 1.02 m for 25 Joule.

The preliminary tests showed that with a falling height according to the standard of 1.02 m the knife goes through all structures and the differences cannot be seen. Also a height of 0.61 m gave no significant differences. To find out differences between the fabrics,

the falling height was reduced to 28.5 cm, which is equal to 6.9 Joule for the following test series. With respect to this, the test speed was also reduced, due to

$$v = \sqrt{2 * g * h} \quad (3)$$

Where v represents the velocity of the falling knife in m/s during the test. According to this equation, the test speed for a height of 1.02 m is 4.47 m/s, but for the height of 0.28 m a reduced speed of 2.34 m/s was measured.

$$\Delta E = W = \int_{s=0}^{s=d_{penetration}} F(s) \cdot ds = F_{average} \cdot ds \quad (4)$$

The kinetic energy E_{KIN} , which occurs during the test results of these adjustments like the following:

$$E_{KIN} = \frac{1}{2} * m * v^2 \quad (5)$$

For the falling weight of 2.5 kg and the height of 0.285 m the mean impact force will be calculated like this:

$$F_{average} = \frac{\Delta E}{d_{penetration}} = \frac{m * g * h}{d_{penetration}} \quad (6)$$

Where $d_{penetration}$ is the stab depth of the knife in the plasticine.

$$\Delta E = W = E_{KIN} = W_C + W_{PP} + W_{FBY} + W_{FCY} \quad (7)$$

where W_C is the cutting work, W_{PP} the work to penetrate the plasticine, W_{FBY} the work of the friction between the yarns and W_{FCY} the work of friction of the cut yarns. From initial tests with pure plasticine without fabric, the knife goes through the complete plasticine, so we can assume that the energy loss for W_{PP} is a negligible part of the complete energy during this penetration. The energy of friction between the yarns and the energy of friction during the cutting are in this case also negligible, because for the practical evaluation it is important to have an idea about the average resistance of the fabric against penetration. This average force is a calculated value, which would correspond to the force if the penetration speed is constant, according to equation 7 and can be used for the comparison of different fabrics. This force accumulates all above mentioned influences and resistances, which are important during the development and

optimisation of the fabric, but for the final evaluation the average penetration force is relevant.

This is an important factor to demonstrate the interdependence between the stab depth results and the impacted energy, which leads to fewer injuries during the stabbing.

The drop height is measured as the distance between the tip of the blade and the box with plasticine, which is defined as L_2 , like shown in Figure 1-13.

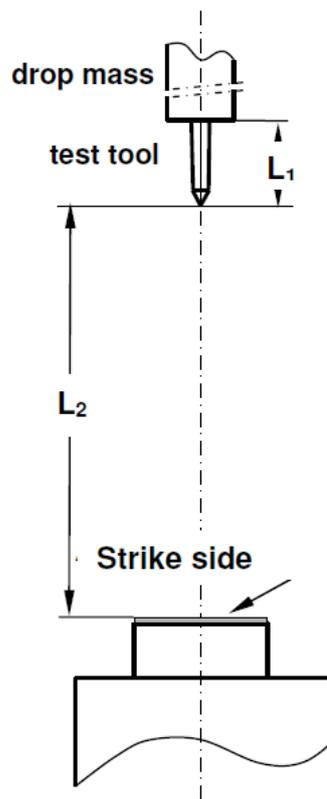


Figure 1-13: Schematic view of the drop height (Test Standard VPAM KDIW 2004)

The penetration depth of the blade in the plasticine is measured with a ruler. Therefore the resultant hole is excavated. According to the standard, tests are carried out three times per sample. The evaluation of the test results are explained as follows:

1.8.2 Evaluation of measurement results

The VPAM stab resistance tests (Test Standard VPAM KDIW 2004) are carried out with a standard knife which falls from a specific height, depending on the required energy level. Therefore it is driven by a defined weight onto the test sample, which is

lying on a box with ballistic plasticine. The penetration depth in the plasticine is measured after removing the plasticine on one side of the penetration channel. Due to the correlation of blade width and length in the front part of the blade, additionally the width can be measured and the depth can be calculated out of it. Figure 1-14 shows the dimensions of the knife and Figure 1-15 the original blade, like it is used.

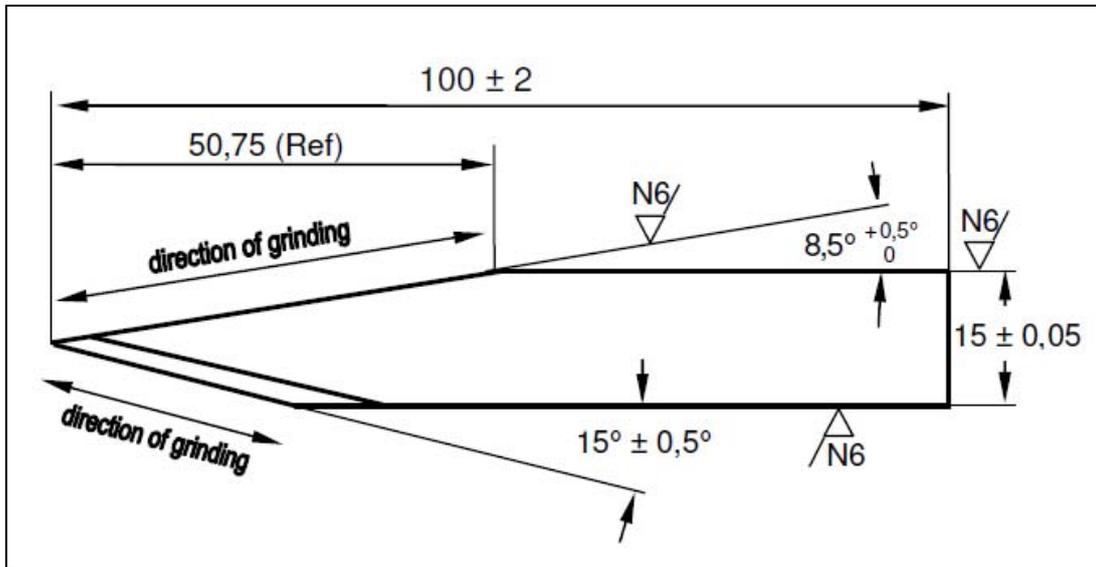


Figure 1-14: Standard test knife (Test Standard VPAM KDIW 2004)



Figure 1-15: Standard knife blade

According to the Guideline the deformation depth is determined by measuring the deepest point of the stab impact, where the trauma impact isn't taken into account. This means that the hole, which is caused by the stab test, has to be dug out carefully and the exposed hole has to be measured using a ruler.

1.8.3 Cut methods

In these chapters the most important and applied cut test methods are described.

1.8.3.1 Couptest

The EN 388 is the current European Standard for "Protective gloves against mechanical risks". It specifies the test methods for protective gloves against abrasion, cutting, tearing and puncture. The examination of the cut resistance is based on a cut with a circular rotating blade that moves back under specified load on the test specimen and moves back and forth and rotates counter this movement. The repeated contact with a sharp object at low compressive load is described. This test and the testing apparatus are in practice also known under the name "Coup test". The result of cut resistance is the ratio of the number of required cutting cycles to average the test and control material. The result is classified in cut resistance classes from 0 to 5, with 5 representing the highest performance level.

Despite the consideration of the sharpness of the blade, the suitability is questioned. In particular, through the use of high power or hybrid yarns, this test method seems to have reached its limit. This leads to highly determined "Schnittschutzlevel" at unacceptable reproducibility. The first negative way of influencing the results and reproducibility is in the general apparatus. Although the requirements are defined and described in the EN 388, the devices are specially manufactured to order. Differences in structure may thereby affect the test values. Another negative impact on the comparability of the results can be the specification of the standard cotton fabric. Minimal differences in the quality of a batch can already influence the average index. Secondly, it is not ensured that all test centres use an equal power reference sample. Problematic is also the circular blade used. As a result of difficulties in obtaining the predetermined force, the quality is no longer guaranteed. The change type, hardness and cutting characteristics influence the test results. Studies show that there are prohibitively large differences in the sharpness of the blades. Reliable reproducibility is thus not given. With a knife of hard inorganic components, the service life of the blade is greatly reduced. The blade is dull and there is a change in the cutting action. This has the result that more cycles are required to the average score of the sample. This gives a poor and not reproducible result (Zuther 2011).

1.8.3.2 Tomodynamometer

The EN ISO 13997 comes from the field of protective clothing. It includes the "Determination of resistance to cutting by sharp objects". The force is determined, which is required to sever the sample material in a movement over a set distance of 20 mm (reference distance). The test result is expressed in Newton (N) and is tested on a dynamometer Tomo (TDM-100) interface testing machine. In contrast to the EN 388 there will not be a rotating circular blade, but a straight blade used in this test method. As with the EN 388, a conductive material is placed between textile and adhesive tape and connected to the frame. Once the blade cuts through the test material, it comes into contact with the aluminium foil. The resulting electrical circuit stops the test automatically.

The advantage of the procedure according to ISO 13997 compared to EN 388 is that the blade does not need to be replaced after each test. In addition, there is a resist holender contact between specimen and blade, but only a single contact. An influence of the test results from abrasive effects of, for example, inorganic fibres is minimized. A disadvantage is the relatively high price of checking because for each cut a new blade is required. The EN388 test is cheap the circular blades can be used several times. In addition, the test performance is simple and fast. A major disadvantage of the test methods is the fact that it is checked only in one cutting direction. Thereby no information on a possible isotropic cut resistance is possible.

1.8.3.3 Cut Protection Performance Tester CPPT

The ASTM F1790 is the American standard for measuring the cut resistance of materials for protective clothing. (F1790) For the cutting test, a machine called Cut Protection Performance Tester, called CPPD is used. The CPPT differs from the structure and the cutting speed of ISO 13997, but is otherwise comparable.

1.8.4 Frictional test parameters

The friction behaviour of fabrics has to be split in two areas. First there is the friction behaviour itself, which includes the fibre, yarn and fabric friction. The second parameter is the yarn pull-out test. This test is a practical method to investigate the material properties of a fabric. It provides useful information about the fabric's deformations and its ability to absorb energy, especially protective applications and therefore the frictional behaviour of the fabric (Asayesh et al. 2012). It is influenced by

many mechanical properties like the yarn geometry and fabric weave structure (Pan, Yoon 1993). A similar test to the pull-out test is the seam slippage. Here yarns are also pulled out of a seam. It is explained in detail after the other methods.

1.8.4.1 Friction

The performance of textiles is greatly influenced by its frictional behaviour. Due to the smooth surface of aramid fabrics, the stab resistant performance is affected by textile frictions and their influencing factors (Ramkumar et al. 2005). They have to be taken into account to increase stab resistant properties. The influencing factors of textile friction behaviours can be divided into fibre friction, yarn friction and fabric friction.

1.8.4.1.1 Fibre friction

Fibre friction is related to the structural parameters and the bulk properties of fibres. Fibre structural properties can be the crimp, or in case of wool, the scales type and size, the fibres surface roughness or the molecular orientation. Some bulk properties are for example the diameter, the fineness and the length of the fibres. Also the fibre material itself influences the frictional behaviour. To determine the fibre-to-fibre friction and fibre-to-other surface friction, also the test conditions have to be taken into account (Hong et al. 2004).

1.8.4.1.2 Yarn friction

Yarn friction is related to both surface properties and bulk properties of yarns. Yarn friction is determined by the before mentioned fibre parameters and the yarn structure and bulk parameter, like yarn twist, spinning method (Ramkumar et al. 2003) or yarn fineness. The coefficient of friction of yarn increases with an increasing yarn linear density, due to the larger contact area and with an increasing yarn twist of ring and rotor spun yarns, friction decreases for different materials. High twist results in a smaller area of contact, and thus results in a lower frictional force. The yarn friction decreases with an increased roughness of the yarn surface. However, with a very rough yarn surface and increased unevenness, the yarn friction tends to increase.

Also here the test conditions to determine the frictional behaviour of yarns are important, like the normal load, the frictional speed, contact geometry and the boundary conditions (Ramkumar et al. 2004; Ajayi, Elder 1997). On top of that the friction of the yarn is also influenced by finishing (Hwang et al. 2015).

1.8.4.1.3 Fabric friction

Fabric friction is related to both surface properties and bulk properties of fabrics. Parameters affecting the fabric structure are the weave pattern and the fabric finishing (Bazhenov, Goncharuk 2014). Twill weave pattern show higher friction forces than plain weave pattern, due to the floating length of the yarns (Behera, Hari 2010; Ajayi 1992). The influence of operational parameters, like load pressure or the sliding speed, was reported by several researchers (Ajayi, Elder 1997; Abghari 2011; Arshi et al. 2012; Hermann et al. 2004; Mihail 2015).

1.8.4.1.3.1 Friction measurement

In general the friction is the force that opposes the relative motion of two surfaces in contact with the friction coefficient μ .

The frictional force F is mainly determined by the nature of the surfaces which are in contact and the force that holds the surfaces in contact, which is known as the normal force. The friction is governed by Amonton's laws with: (Saville 1999)

$$F = \mu \cdot F_N \quad (8)$$

After Coulomb the friction is divided into static friction and sliding friction, which can't be separated strictly, because they can occur simultaneously or alternatively. It is the force, which is required to move a carriage on the surface of a test sample to determine the coefficient of static friction and kinetic friction. When a resting object starts to slide, a force is required to start the object moving. It is known as the static friction. The static friction force is proportional the normal or pressing force F_N :

$$F_S = \mu_s \cdot F_N \quad (9)$$

The coefficient μ_s is the coefficient of static friction. It depends on the material combination, but has on the other hand almost no dependency of the contact area of the surfaces. Already Coulomb has determined that μ_s increases with the lifetime. Once the object is moving, the force required to keep it moving is lower than the original starting force and is known as sliding or dynamic friction. This movement in total is defined as the frictional force. The frictional force F_R is independent of the size of the contact area and increases mostly linear with normal force F_N . The coefficient of friction μ depends on the surface (EN 14882:2005; Langston, Rainey 1954; Timble 2014).

The sliding or kinetic frictional force F_K is the force, which acts after overcoming the adhesion. Coulomb has found experimentally that the sliding friction is proportional to the pressing force N and has no significant dependence of the contact area and roughness of the surfaces. The kinetic coefficient of friction is approximately equal to the static friction coefficient:

$$\mu_K \approx \mu_S \quad (10)$$

Hereby the sliding friction depends not, or only very weak, on the sliding speed. These laws are practicable well for hard materials, but not for textile materials particularly at low values of normal force. In most cases it is the sliding friction that is of practical interest. To analyse the sliding process, several operational parameters which can influence the results of the friction, are determined.

1.8.4.2 Pull-out

The pull-out effect is defined as the force, which is required to pull out one single yarn out of the fabric structure, calculated as the sum of the frictional resistances at the crossing points to overcome (Kirkwood et al. 2004; Bilisik 2011). Friction in turn is most dependent on the linear density and the pattern (Rebouillat 1998).

The required force to pull out the yarn is more, the higher the friction coefficient is. Some energy has to be mustered to move and displace the yarns out of their structure and this leads to a higher energy absorption by the fabric (Cheeseman, Bogetti 2003). The resistant energy which has to be overcome is due to friction forces. The friction of the fabric plays a role, especially for lower impact velocities. There the frictional forces at the yarn crossover points lead to the destruction of the fibres, which happens under energy absorption. A higher fabric density will lead to more energy absorption, because crossover points represent a higher resistance in form of friction (Bilisik, Korkmaz 2011). If the friction between the yarns is too high they would rather cut each other than displace themselves. In case the friction is too low, there is no resistance against the impact and yarn slippage occurs. Therefore the coefficient of friction has to be high enough that yarns cannot be easily pulled out or moved aside. Some coefficients of friction for interyarn friction, depending on the absorption capacity are (Zeng et al. 2006)

- $\mu = 0.0 - 0.06$ for low friction forces
- $\mu = 0.06 - 0.2$ for medium friction forces
- $\mu = 0.2 - 1.0$ for high friction forces

A high coefficient of friction leads to additional energy absorption, because more energy is required for the pull-out force. The friction forces between aramid yarns decrease in the state of wet yarns, because the blade can slide through easier and therefore lead to a lower protection level (Bazhenov, Goncharuk 2014).

1.8.4.2.1 Pull-out measurements

The pull-out mechanism means that one yarn is pulled out of a fabric structure by motion of the penetrator (Bilisik 2011). The mechanism is shared in two areas. In the beginning of the test, the yarn has to be uncrimped. A high crimp of the yarns in the fabric structure leads to a high energy absorption which is important for mechanical impacts (Sadegh, Cavallaro 2012). The second region is the yarn translation region. Figure 2-82 presents the effect on the yarn, when it is uncrimped before the mechanism of yarn translation starts (Guo et al. 2014).

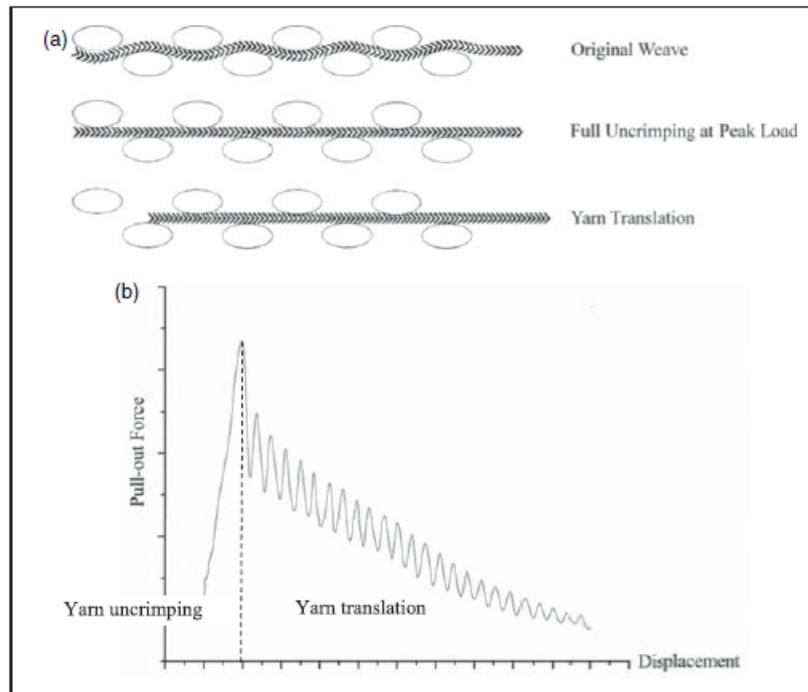


Figure 1-16: Principle of the Pull-out measurement after Guo (Guo et al. 2014)

After Bilisik (Bilisik 2011), the test is split in two regions, the static and kinetic region. He divided the static region again into two areas; the area, where the crimped yarn expends till it is uncrimped, and the fabric displacement region, which is the extensional stress in the fabric area, when a yarn is pulled out. In this region, the force increases to a maximum value, which corresponds to the maximum static friction force F_s . The kinetic region is the motion, when the yarn is pulled through all crossing points. Hereby a stick-slip effect occurs. Stick is the moment, when a warp yarn is passing over or under a filling yarn. The slip area is the area between two picks. (Bilisik 2012) This region corresponds to the dynamic or kinetic friction force F_k . The different regions are presented schematically in figure 1-16.

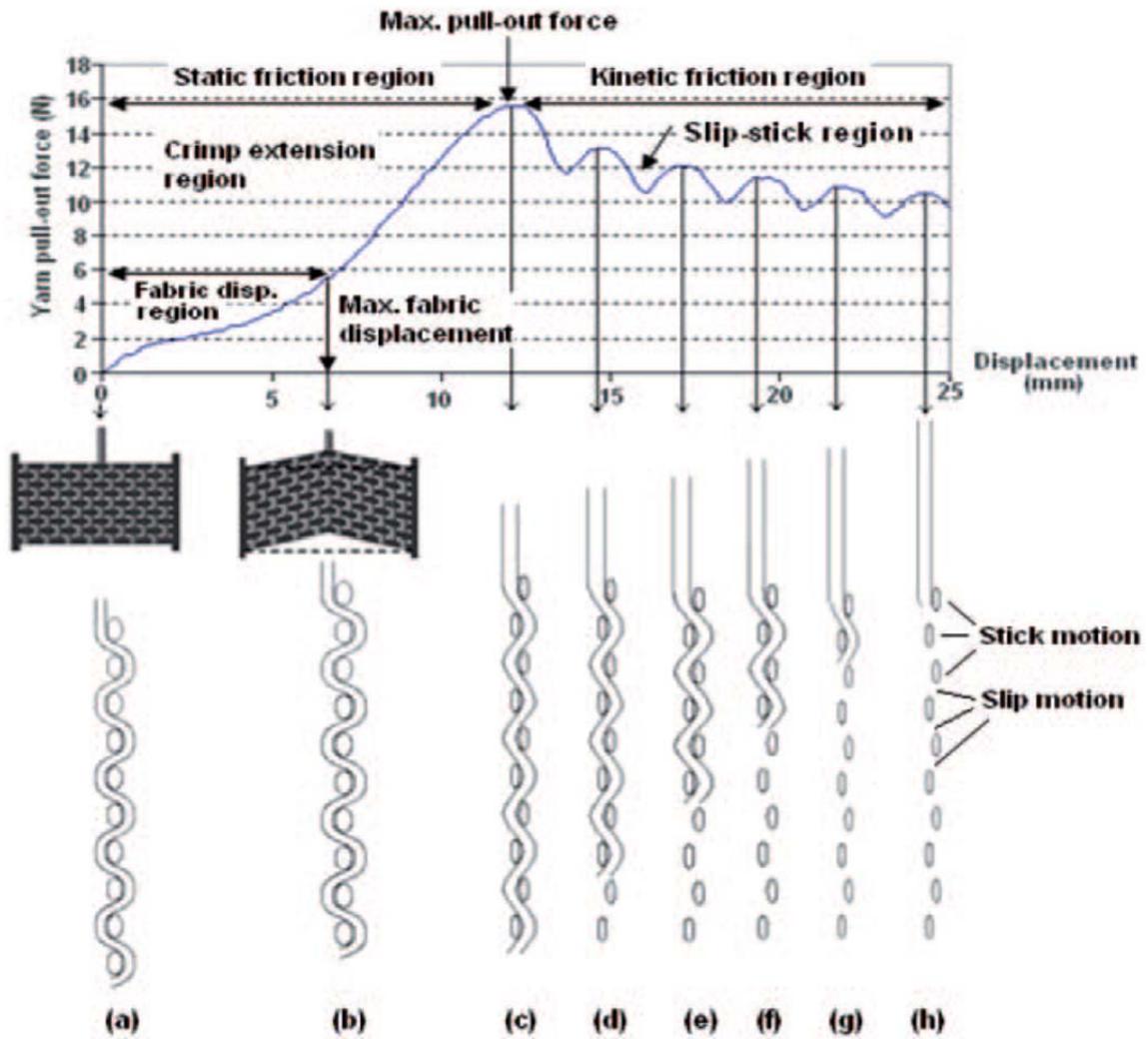


Figure 1-17: Principle of the Pull-out measurement after Bilisik (Bilisik 2011)

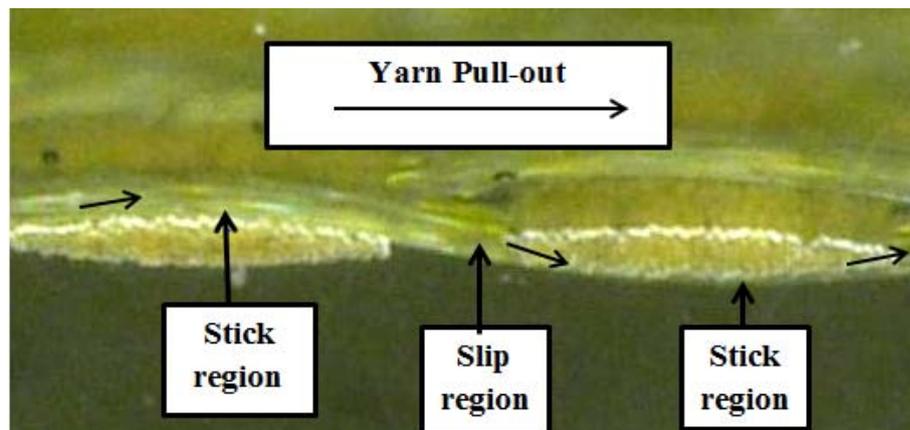


Figure 1-18: Stick-slip regions

The measurements are presented idealized. Local effects are neglected, because they are too small in comparison to the yarn pull-out forces (Pan, Yoon 1993). Also it is

assumed that the axial tension is dominant, so the shear stress can be neglected in comparison to the movement at the crossing points (Pan, Yoon 1993).

Other researchers made tests, where they found out, that the yarn pull-out is dependent on the fabric density, the number of pulled yarns and also the sample size (Bilisik 2013). Tight fabric structures show higher values than loose structures. Additionally, the impact energies are absorbed by the friction between the yarns (Bilisik, Korkmaz 2011). Also the test methods are quite different. One method is to clamp the fabric at the sides and one or more yarns are pulled out (Bilisik 2011). This leads to extensional stress in the fabric area, like shown in figure 1-18. Guo carried out pull-out tests with the out-of plane method, where the thread is pulled out of the fabric surface (Guo et al. 2014). The inter yarn friction decreases with the remaining number of crossing points (Guo et al. 2014). Also the pretension influences the pull-out rate. Results lead to a higher pull-out load if the pretension is smaller (Nilakantan, Gillespie 2013).

1.8.4.3 Seam slippage

In the quality evaluation of ready-made garments is the slippage of yarn at the seam an important factor. The seam slippage can be defined as the ability of the displacement of yarns, where the yarns in the fabric slip away from the seam under stress, what means, that the weft yarns slip over the warp yarns or the warp yarn over the weft yarns crosswise to the seam, occurred through a given load and cause an opening of the fabric, like the example in Figure 1-19 shows.

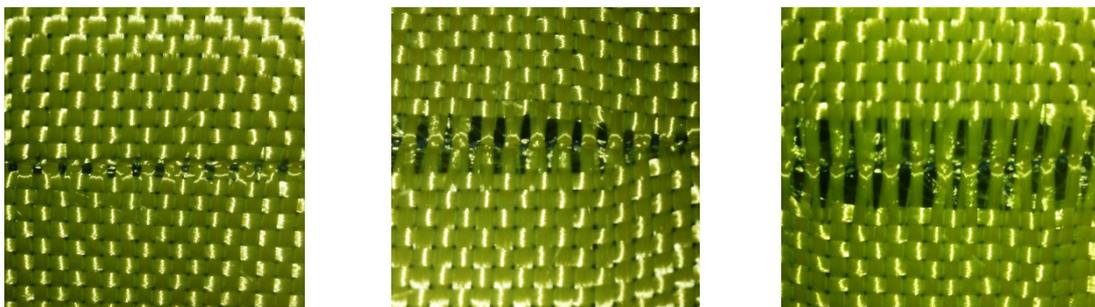


Figure 1-19: Seam opening of fabric P170

The value of the seam slippage is expressed as the seam slippage resistance F_S , which is the force to open a defined seam L_S through the displacement of yarns crosswise to the seam direction (Reumann 2000).

It can be defined as:

$$F_S \approx F_{\Sigma L_S} \quad (11)$$

With ΣL_S = Sum of openings to both directions in the seam area

This phenomenon leads to a reduced range of the end-use of possible areas. The characteristic of migration or slippage is an important parameter and depends on different fabric structure properties, like fibre type, pattern, the linear density of the yarns and the number of yarns per unit length, but also the thread seam construction and stitch density (Milašius 2012). One important factor is also the yarn-to-yarn friction. Especially very smooth fibre types lead to a high yarn migration, particular in the seam area during high stress. Resultant of this, it is assumed, that the yarn friction is linked to the seam slippage (Daukantiene, Lapinskienė 2012; Behera, Hari 2010; Malčiauskiene et al. 2011). The seam slippage will decrease by higher friction forces (Backauskaite et al. 2013).

In the area of stab resistance of textiles, special for high strength fibres like aramid, the effect is given, that during the penetration with the knife, the yarns are not cut; they migrate and cause an opening of the fabric. This phenomenon is given for all smooth fibres, which are penetrated by a sharp shape like a knife. The aim of this chapter is to analyse the interdependence between this displacement and the seam slippage, because it is assumed to be similar to the seam slippage.

1.9 Conclusions

The analysis of the state of the art showed, that a lot of research has been done in the field of protective garments against stab attacks. The need for stab resistant materials, the materials which are currently used for slash and cut resistant applications and their properties were reviewed in the state of the art. A main problem of these materials is the missing friction behaviour, why a knife can penetrate a fabric easily. Therefore a lot of layers are used to ensure adequate protection, but this leads to bad comfort behaviour because of stiffness and heaviness. Also the test procedures to define the protection level are incomplete or for improvement.

Therefore this thesis deals with several focal points. First of all, the stab resistant measurement itself is analysed to find out the weak points, which have to be improved. Then test trials will be carried out using various fabrics, to find out the influential parameters which affect the stab depth. These test parameters are analysed in following, with an analysis, how to test them and where are the limitations in testing. Some test procedures are improved.

Another focus lays on the fabrics itself, which will be improved in order to reduce fabric layers and improve the comfort of them.

The last step will be a comparison of test results to simulations of the stabbing behaviour. The goal is to develop lifelike simulations to give predictions of the behaviour of new fabric developments.

CHAPTER 2

EXPERIMENTAL WORK

2 Experimental work

2.1 Introduction

In the previous chapters, the materials and methods, which are currently used for stab resistant applications and also their properties, were described. It was shown, that a main problem of these fabrics is the missing friction interaction between the yarns, why a knife can penetrate these fabrics easily. To guarantee the safety of the wearer, many layers have to be combined which leads to a high weight of the safety vests and consequently a lower comfort for the wearer like mentioned before.

An aim of this work is to analyse the influencing parameters of stab penetration and to develop fabric combinations, which resist better against stab attacks.

In this chapter the stab measurement itself is discussed and boundaries of the method are shown. Resultant of this, some improvements were done and presented in order to get reliable and reproducible results. Afterwards an experimental investigation of stab penetration into body armour is conducted. Therefore the properties of different fabric types are compared, which influence the stab resistance using a standard stab test method. Like discussed in the previous chapters, wool takes a positive influence on the comfort of stab resistance fabrics (Mahbub 2015), but the influence onto the stab resistance wasn't analysed. Therefore wool is added to the fabrics, which are determined in the following chapters and combined with the armour test panels.

Also test parameters, which can influence the stab resistance, are determined experimentally to find better solutions in testing. Therefore evaluation methods are improved and described. Then the influencing factors, which influence the stab depth, are explained in detail and test series are made to find out the dependencies of the stab depth in order to investigate key variables of the knife-armour interactions. After an analysis of the data, improvements in test methods are presented and compared to the standard methods and materials.

2.2 Materials

The main high performance fibres, which are commonly used for stab resistant fabrics are para-aramids and UHMWPE fibres, which were explained before. This work focusses on one fibre type of this group, because the main focus is to compare the properties of one fibre type. As aramid is most used in this field, this fibre was chosen for the following investigations. In

order to investigate the penetration of knives into various test materials, five different aramid fabric types were used in these trials. This set of materials was chosen to simulate some of the actual and proposed armour materials for stab resistant garments and to cover a wide variety of fabric properties. In addition, a wool fabric was analysed and combined with the aramid panels. Table 2-1 gives the fabric descriptions and lists the properties of the armour and wool materials.

Table 2-1: Properties of aramid fabrics

Fabric code	Structure pattern	Yarn Count		Threads		Mass g/m ²	Thickness mm
		tex		per cm			
		Warp	Weft	Warp	Weft		
P61	Plain	22	22	14	14	61	0.10
P170	Plain	127	127	7	7	170	0.28
P230	Plain	158	158	7	7	230	0.33
T170	Twill	127	127	7	7	170	0.27
T230	Twill	158	158	7	7	230	0.36
Wool	Twill	52	52	23	19	249	0.58

2.3 Methods

2.3.1 Measurement of stab resistance

The German standard VPAM KDIW (Test Standard VPAM KDIW 2004) is the most common used standard in Germany and is also applied by the German police, why this test standard is chosen for the test trials.

2.3.2 Principle of stab measurement

According to the VPAM KDIW (Test Standard VPAM KDIW 2004), a test sample is placed onto a plasticine box and stab tests are carried out. The penetration process has been already explained in detail in chapter 1.8.1. A blade of a defined sharpness and size drops from a defined height which depends on the energy level for the stabbing impact. The penetration depth is measured afterwards.

2.3.3 Boundaries of stab measurement

In practice, this measurement method is, however, quite difficult to implement and leads to frequent discarding of the stab. When digging, it may happen that the stab hole is touched and so falsifying the measuring result or becomes unusable. While three samples should be measured according to the standard and to ensure reproducible and meaningful results, it becomes quite difficult and expensive to get enough test material in case of the discard of many measurement results. Therefore some users measure the cutting width on the surface of the plasticine and it is shown, that the results are comparable and the cutting width is a more reliable parameter for the stab resistance measurements than the penetration depth. (Aumann et al. 2013; Ehrmann et al. 2013) This method gives also no information about the trauma effect. These problems led to the development of a more productive method of measurement, where the determination of the stab depth is done easier and the information about the trauma size is given. Also other boundaries in the test standard are analysed. There is no information about the sample size and a pretension of the test samples. Another problem is the usage of the knife. According to the standard, it is just allowed to use a knife one time. This missing information are analysed and added to a new test method, which is developed in scope of this work. Therefore test series are done to analyse the sample size, the pretension and from economic view, the tear of the knife is also analysed in a test series.

2.3.4 Development of a new evaluation method of measuring the stab depth

The new evaluation method is described, where the deformation depth and the trauma can be poured out in plasticine and the deformation of the lowest fabric layer can be fixed. Thereby the puncture can be measured accurately and fixed plastically. The plasticized samples can also be measured in order to analyse and simulate movement, deformation and energy absorption.

When preparing the test run small cups need to be filled with plasticine. It is important to consider that no air bubbles emerge. The cup is worked into the background material just below the knife tip. Then, a measurement sample has to be positioned on top of it, and the test is performed by dropping the knife from a specified height. To fix the lowest fabric layer after it is penetrated, the upper layers have to be removed carefully and it must be ensured that the lowest fabric layer remains in its position. Subsequently, the cup can be carefully removed. First, the deformation of the fabric is fixed with quick-drying adhesive. After the hardening of the adhesive, the puncture in the plasticine is poured out and after hardening of the resin, the

trauma can be filled with silicone. Using cups allows the testing of multiple samples in succession and simultaneous processing. Thus, the individual steps must not be carried out directly after each test. Another advantage is that there is no need for time-consuming digging out of the puncture, which in addition leads to a low success rate as the results will be damaged easily. Using this method, measurable samples are available in a short time. Due to their three-dimensionality, the poured out puncture and the trauma of a sample can be easily compared with those of another sample. This method is also useful for the pure measurement of the penetration depth because differences between each sample can be recognized and assessed visually. In the following, the individual processes are explained in detail.

2.3.4.1 Deformation of the lowest fabric layer

In order to preserve the deformation of the fabric permanently, which is caused by the puncture, it is fixed with adhesive. This is done by wetting the fabric layer by a pipette with collodion. To obtain a particularly good and stable result, several layers are coated with collodion. Once the adhesive has dried, the prepared fabric layer can be removed from the plasticine.

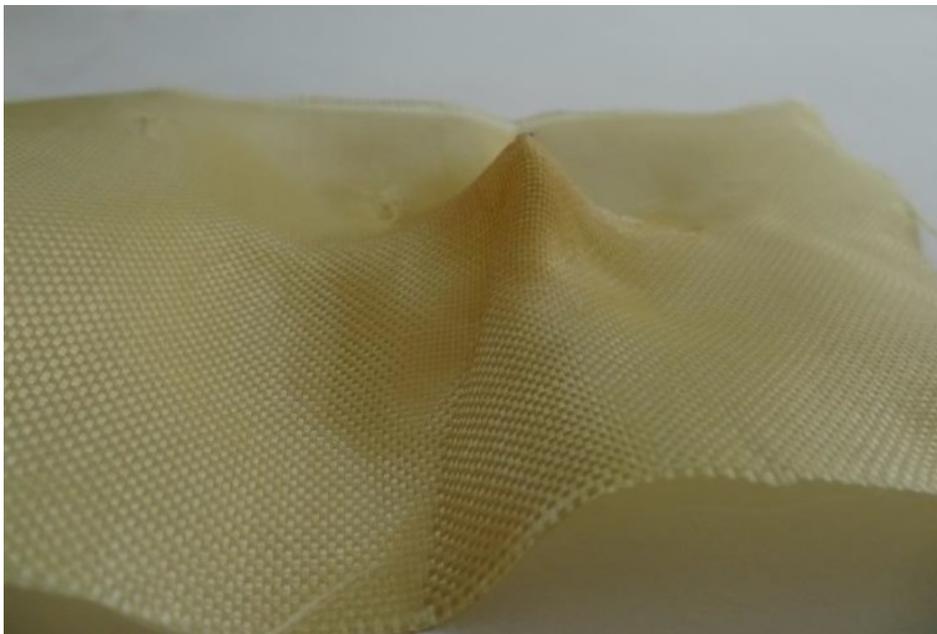


Figure 2-1: Fixed deformation of the fabric

Figure 2-1 shows a hardened fabric layer of aramid, which was tested against puncture resistance. The fabric layers, which are fixed like this, allow the possibility to compare the different kind of deformations of various materials, pattern or densities of fabrics.

2.3.4.2 Deformation depth of puncture

The performed methodology simplifies the measurement of the deformation depth and enables rapid processing of multiple samples simultaneously, since the individual measurements are carried out in removable cups. First, an epoxy resin composition with a mixing ratio of 8:1 is prepared and used to pour it into the groove. The resin is filled in dropwise with a spatula into the puncture. Thereby it has to be ensured, that the resin can completely flow into the puncture and bubbles have the opportunity to escape. To pour the trauma completely with the resin, it is important to fill it accurately up to the puncture beginning. The used epoxy resin has a curing time of approximately twelve hours. After this time, the sample is ready for further processing and can be removed out of the plasticine.

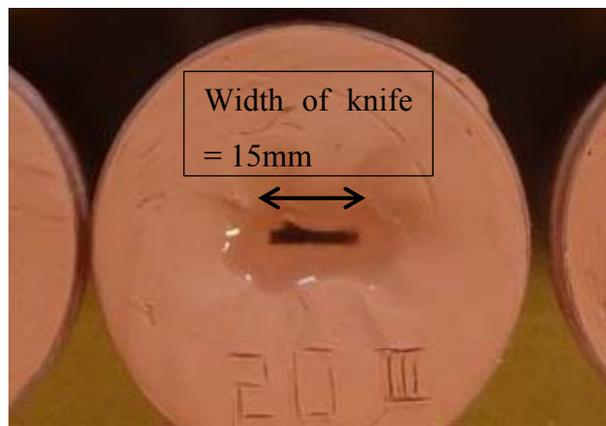


Figure 2-2: Puncture holes filled with resin

Figure 2-2 shows the plasticine filled cups with the pour out punctures. After the drying time, it is possible to dig them out like the following Figure 2-3 shows and to measure the penetration depth of the blade on the straight side of the knife.

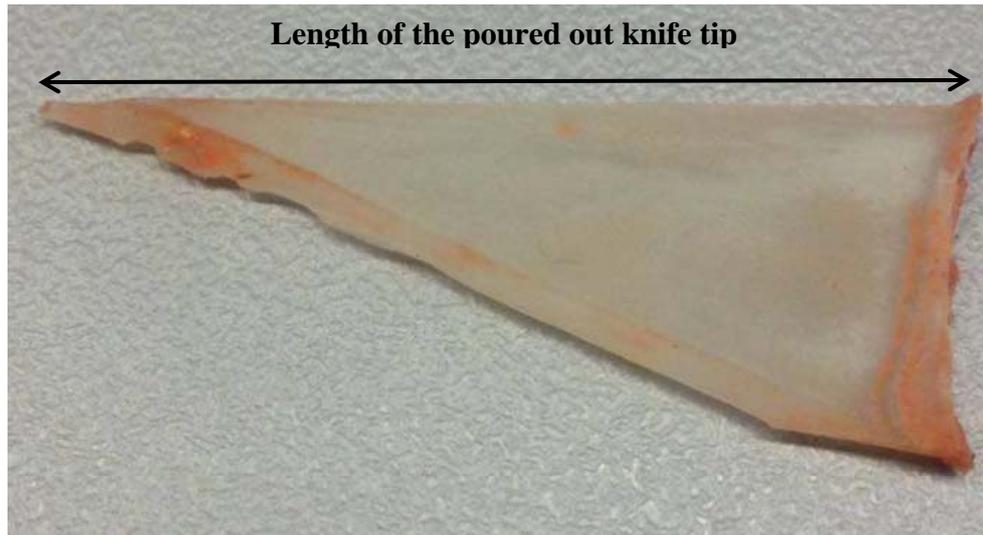


Figure 2-3: Shape of the knife tip

In addition to this simple measurement, three-dimensional models of the pour out punctures were prepared. Figure 2-3 shows, how exactly the puncture was poured out. The cut surface of the blade is exactly recognizable and also the beginning of the trauma can be seen. It can be constructed as the stitch can be attached to the trauma, to visualize the action of the knife and the impact energy. To compare the model with the blade, Figure 2-4 shows the standard knife, which is used for testing the stab resistance according to VPAM.

2.3.4.3 Deformation of trauma

In addition to the penetration depth, it is possible to fix the resulting trauma. Here, a silicone compound is filled directly into the deformation in the plasticine.

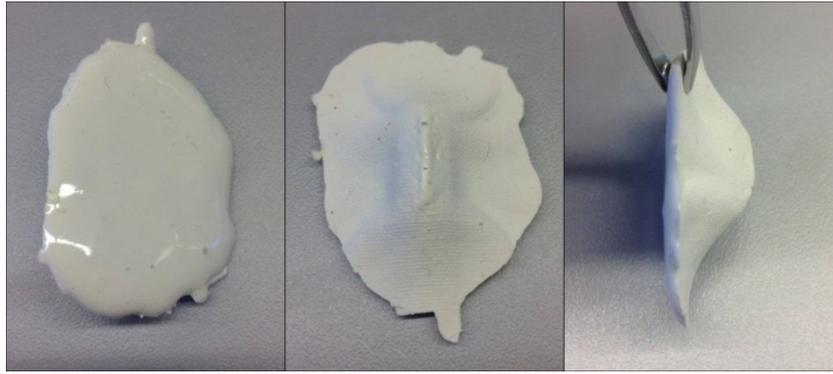


Figure 2-4: Fixed trauma

These results allow the comparison of different materials in their trauma building behaviour. This can be done optically, but also by measuring the diameters using a digital microscope or a measuring instrument.

With the values weight and density, the volume can be determined to compare different samples in their energy absorption behaviour like the following:

$$V_{[cm^3]} = \frac{m[g]}{\rho \left[\frac{g}{cm^3} \right]} \quad (12)$$

Where m is the mass of the poured trauma and ρ the density of the silicone compound material with 1.24 g/cm^3 .

2.3.4.3.1 Conclusion

A new method to determine the stab depth but also the kind and size of trauma is presented. It is shown, that the new method is not as error prone as the method that is used according to the standard. It can be avoided error measurements, resulting in performing accurate and efficient results. Fixing the fabric layers, allow the possibility to compare the different kind of deformations of various materials, pattern or densities of fabrics and can be compared to simulations of stab impacts in order to get realistic simulations.

The fixed trauma out of silicone compound allows the comparison of different materials in their trauma building behaviour. This can be done optically, but also by measuring the diameters using a digital microscope or a measuring instrument. Additionally the volume can be determined to compare different samples in their energy absorption. This gives a higher range of results in order to find better solutions for safety panels out of textile fibrous materials.

2.3.5 Wear and tear knife and reproducibility

According to the standard, a knife is just allowed to be used one time, to ensure unvarying test conditions for all tests. Due to the knife wears during usage, it is assumed, that the measurement results will differ, if the knife is used several times (Watson et al. 2002). But in fact it is not practicable and cost intensive. To assess the blade degradation and determine the wear and tear of the knife a test series with 30 replicates has been performed. To analyse the influence of the fibrous material, two different textile materials have been tested. The already described plain weave aramid fabric P230 and the wool fabric were chosen. To get significant results, four layers of each panel were tested with a height of 24 cm, which is equal to the impact energy of 6 Joule. The data are presented in Figure 2-5.

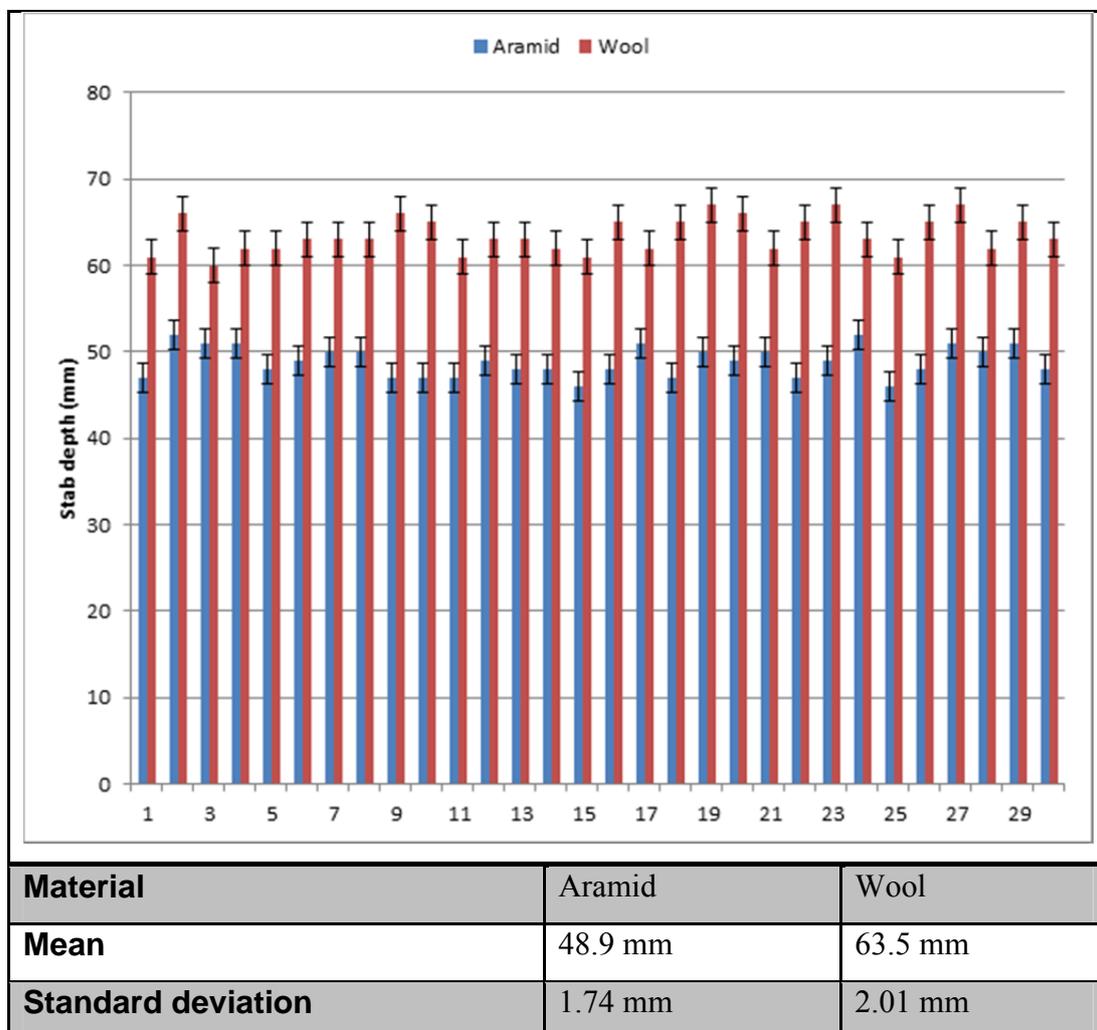


Figure 2-5: Wear and tear of the knife

The effect of repeated use of test blades is seen to be relatively small, like presented in Figure 2-5, where the values for stab depth measurements of thirty single tests are shown. The values

vary between 46 mm and 52 mm for the aramid panels with a mean value of 48.9 mm and a deviation value of 1.74 mm and 60 mm to 67 mm for the wool panel with a mean value of 63.5 mm and a deviation value of 2.01 mm. That means that the effect of wear on penetration depth is not significant.

The aramid test series shows no significant changes in the results. For this reason, a knife was used several times in following test series. For the ensuring of steady conditions each knife has been used a maximum of 10 times.

Not only is the repeated use of the knives an economic problem, but also the number of tests. According to the standard, three tests are carried out at one vest to determine the stab resistance. To analyse, if three tests are enough, in order to obtain meaningful results, the previous test series were analysed in order to see the variations in tests. The standard deviations for the series showed values of 1.74 mm for aramid and 2.01 for wool. The deviation is higher than the trend, why it is assumed, that the number of three tests is enough to get meaningful results and work economical.

2.3.6 Influence Sample size and pretension

The test guideline VPAM KDIW defines only ready-made protective garments in size S to be tested. No preloading force is applied, as the samples are placed on the box of plasticine free of tension. For testing samples out of fabric sections, there are no requirements given in the standard about the size or the pretension. Therefore experiments are carried out to analyse the influencing factors of the sample size and the preloading force. Five sample sizes were tested, starting with a size of 10x10 cm in 5cm steps up to 30x30cm. In order to determine differences in the stab depths, each panel included 10 layers of aramid fabric and the tests were carried out from a height of 0.21 m, which is congruent to an impact energy of 5.03 Joule.

For the pretension a weight of 150 g was chosen, which is split to a similar pretension at all four sides. A higher pretension of the fabric layers would not be realistic, because safety vests are worn over a complete day and should also be comfortable during sitting and may not restrict the wearer.

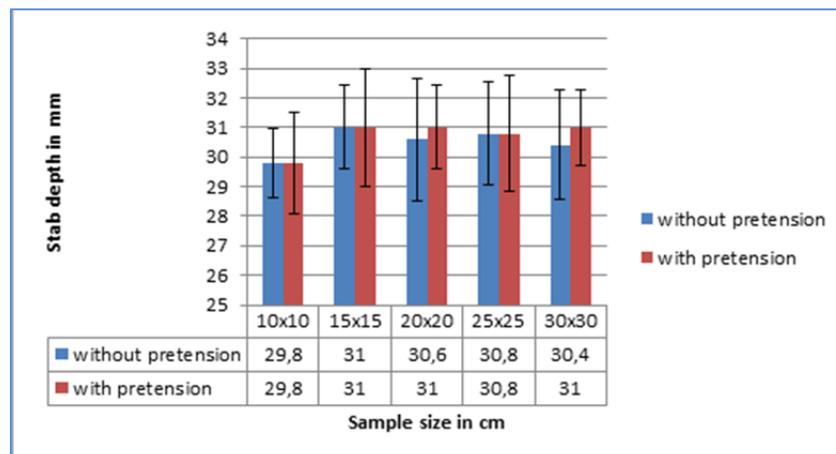


Figure 2-6: Influence of sample size and pretension

After evaluating the penetration depth, no significant differences in the results between the sample sizes are noted and also the pretension has no significant influence onto the results. The sample size of 10x10 cm, 15x15 cm and 25x25 cm provide identical values in both cases. The penetration depth of the pretension sample for the sample size of 20x20 cm and 30x30 cm increases compared to the unstrained sample. Since the sample size did not show any influence on the stab depths, the average sample size of 20x20 cm was chosen for future test series.

Comparing the stab depth with the trauma volume a difference between the samples with and without pretension can be recognized, like shown in Figure 2-7.

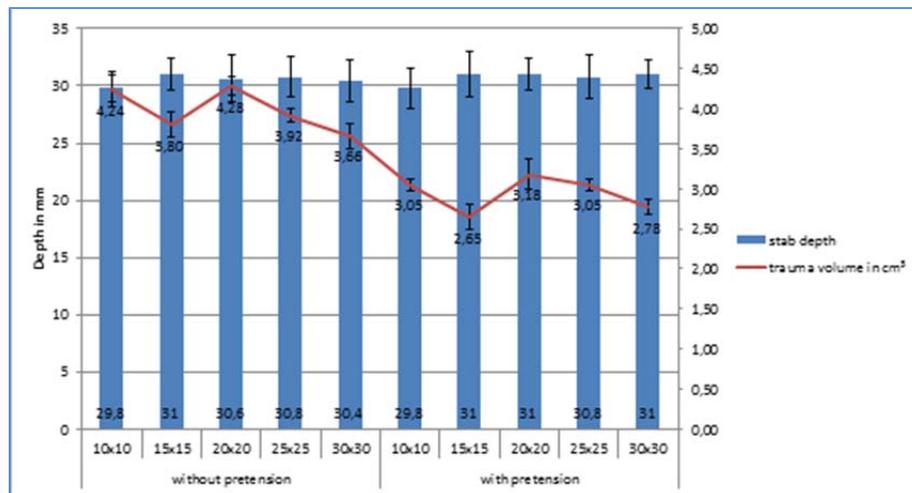


Figure 2-7: Influence of pretension on stab depth and trauma volume

The samples without pretension have a greater trauma, due to the fact that by the relaxed lying on the plasticine surface the samples are carried into the trauma. The weight of the pretension in the second test series leads to a restrain of the fabric during the stab impact. For both test series it can be said, that the sample sizes 10x10 and 20x20 cm almost give the same results in the trauma volume. Apart from this exception, a lower trauma volume is noticeable when the sample size increases.

Due to the fact that the trauma volume is not recognized in the test standards it could be a reason, why there is no specification of a pretension is made.

Not only is the volume of the trauma of interest, but also the depth. It was observed that the depth of the trauma is significantly smaller when a pretension is given, like Figure 2-8 demonstrates.

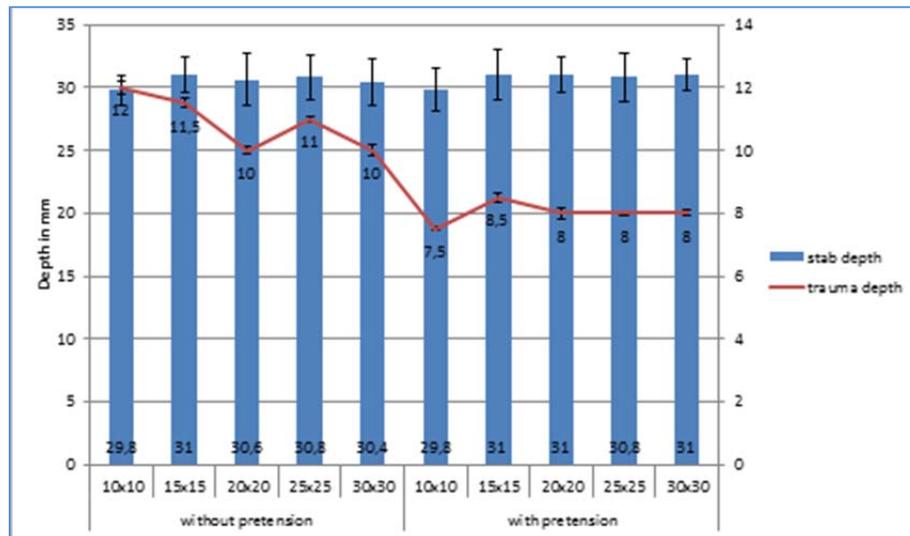


Figure 2-8: Influence of pretension on stab depth and trauma depth

The test series with a pretension show equal results of the trauma depth for all sample sizes. Only a measurement range of 1 mm between the samples is noticeable. Without a pretension, the results of the trauma volumes show a measurement range of 2 mm, while a decrease of the trauma volume can be noted when the sample size becomes larger.

2.3.6.1 Conclusion

To work economically and cost-conscious a series of tests was carried out to analyse the wear of the knife during the stabbing. It showed that the measurement results did not change significantly after a test series of thirty tests. Therefore every knife was used for a maximum ten times in the following test series. Also the number of tests and the influence of the sample size were analysed. In order to obtain comparable and reproducible results, the number of measurements was fixed to three and the sample size to 20 by 20 cm.

Even if the stab depth is not significantly different, a pretension on the test samples prevents an additional trauma effect. An additional trauma can cause injury in form of bruises or fractures. This knowledge should be taken into account, when personal protective garments are designed and manufactured. In this case, tight-fit clothing with a certain tension would be recommended. Although the pattern does not influence the stab depth, it can influence the depth of trauma and thus the kind and severity of the injury.

2.4 Stab resistance of fabric panels

After the principle influence of the stab measurement equipment, the influences of the test conditions and the samples themselves were analysed. First the influence of the impact energy was determined, which means, that different heights of impact were compared. After that, different amount of layers were compared, before the fabric structures themselves were analysed. The examination of the fabric panels was carried out in a multi-layer structure. For this purpose, several layers of fabric were arranged one above the other, and then tested together against stab penetration. The mean value of three tests is always presented.

The test panels were arranged from six to ten layers because with a lower amount of layers no useful differences are visible.

2.4.1 Influence of impact energy and number of layers

First, the influence of impact energy onto the stab depths was analysed, why the stab heights were varied. Relatively low impact energies between 4.5 joules and 9 joules were selected, to find out differences between the patterns. The results are analysed and compared in the following diagrams for one type of fabric. The fabrics having a similar behaviour, so the results will be discussed in more detail for one fabric. For all other fabrics the results are summarized in a table and the single values and graphs are presented in Appendix 7-1.

To analyse what influence the number of layers has on the test results, tests were analysed for all fabric types with panels with different number of layers of aramid fabric.

In the first step, the impact energies were defined according to the calculation

$$W_{POT} = m * g * h \quad (13)$$

and

$$h = \frac{W_{POT}}{m * g} \quad (14)$$

Resultant of this, the heights were chosen as follows:

Table 2-2: Heights of stab tests

Height (m)	Impact energy (Joule)
0.185	4.5
0.245	6.0
0.310	7.5
0.367	9.0

The results are first presented in a diagram where the stab depths and impact energies are compared. Therefore the penetration of the blade is measured after each test, taken as the distance from the rear face of the plasticine surface to the blade tip.

2.4.1.1 Pattern P61

The mean values of the stab depth of the fabric P61 are presented in Table 2-3.

Table 2-3: Mean stab depth results for P61

Energy	6 layers	7 layers	8 layers	9 layers	10 layers
4.5 Joule	24.7	19.7	20.0	19.3	18.7
6.0 Joule	39.7	35.0	35.7	32.0	31.3
7.5 Joule	48.7	43.7	45.3	40.7	40.3
9.0 Joule	52.0	50.3	50.3	48.0	49.3

Figure 2-9 shows a typical rise in stab depths over a range of impact energies.

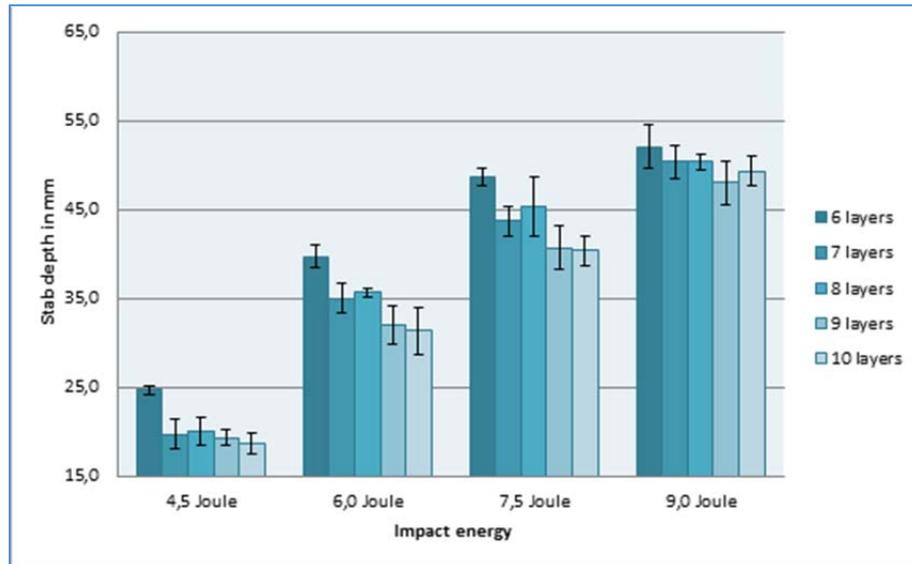


Figure 2-9: P61- Stab depth dependant on impact

It can be seen that the stab depth increases with higher impact energy values. It is also noticeable that the number of layers has a higher influence when using lower impact energies, but this will be analysed in the following chapter. The respective values for all panels will also be analysed in the following chapter. To find out if a linear increase is visible, the data were analysed by using a logarithmic regression analysis. Therefore, a curve was chosen as an example, to demonstrate the approach of the analysis.

The dependency of the stab depth and the impact energy was determined by a logarithmic regression like demonstrated in Figure 2-10. The regression analysis tries to prove a logarithmic relationship between two characteristics to find the best approximation with respect to the points.

The graph of the function

$$y = m * \ln(x) + b \tag{15}$$

is called regression line, where b is called the empirical regression coefficient and the point (x, y) lies on the regression line.

The coefficient of determination R^2 , which can have a value between 0 (no correlation) and 1 (perfect correlation) shows a value of 0.992, which shows the very high correlation between the stab depth and the impact energy.

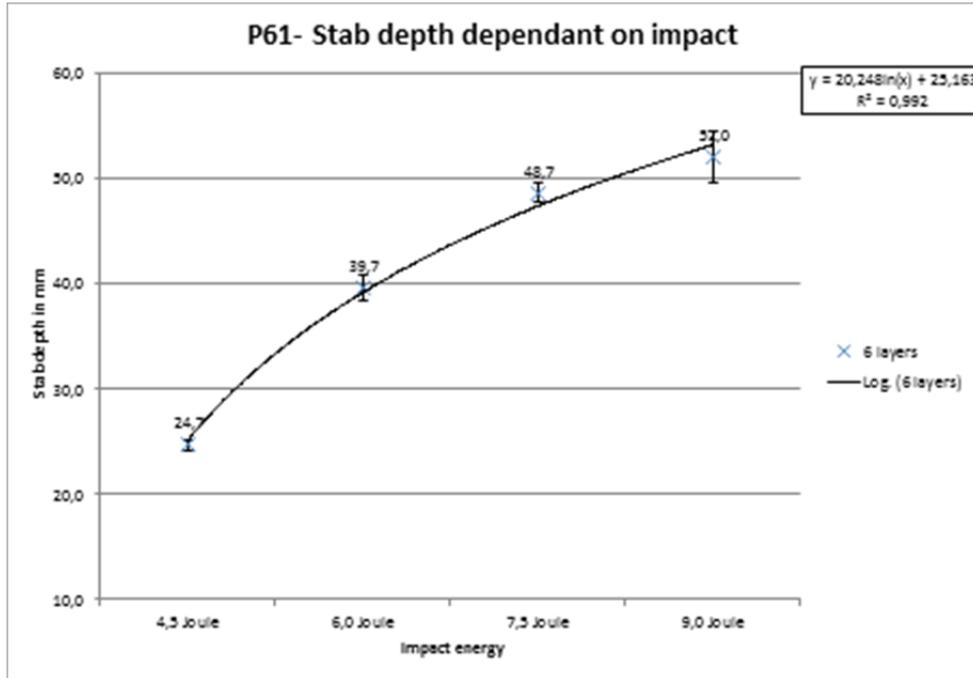


Figure 2-10: P61 - Stab depth of 6 layers

It can be said, that the stab depths increase logarithmic to the increasing impact energies. Figure 2-11 gives the logarithmic curves for the different layer panels of fabric P61.

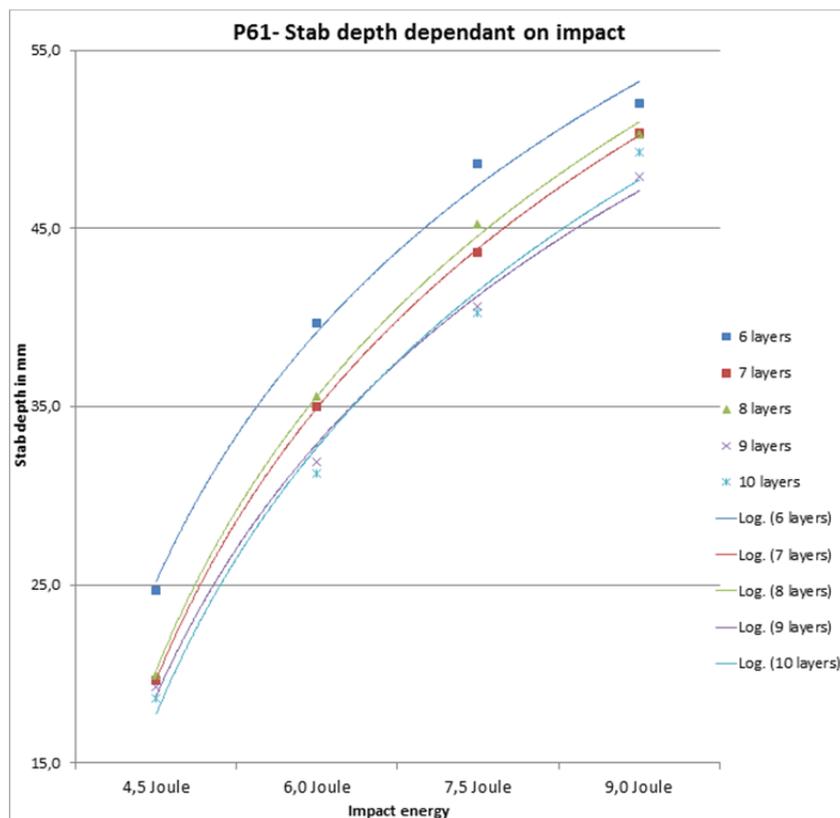


Figure 2-11: P61- Logarithmic curves

Figure 2-11 presents the logarithmic curves of the stab depth results of fabric P61 in dependency of the impact energy for panels from 6 to ten layers. A relationship between the impact energy and stab depth is visible. The coefficient of determination R^2 for all samples represents values of more than 0.95. To see, if all fabrics give this strong relationship between the impact energy and the number of layers, an overview of the coefficients of determination R^2 are given in Table 2-4.

Table 2-4: Coefficients of determination

No of layers	R^2				
	P61	P170	P230	T170	T230
6	0.992	0.977	0.968	0.998	0.984
7	0.999	0.996	0.983	0.996	0.999
8	0.998	0.999	0.997	0.998	0.976
9	0.995	0.997	0.999	0.972	0.980
10	0.987	0.981	0.957	0.995	0.971

It is assumed, that predictions of the stab depth at higher impacts can be taken out of this analysis.

The influence of number of layers was determined at different impact energies. Due to the fact, that the weight of a safety vest is an important criterion for the comfort to wear it, the knowledge about the needed number of layers is of importance.

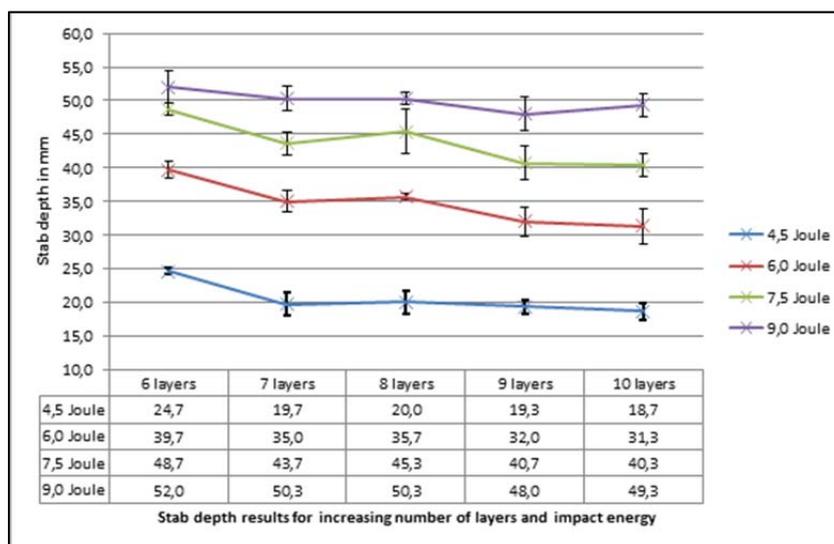


Figure 2-12: P61 - Stab depth of increasing layers

Figure 2-12 shows the effect of fabric layers and impact energy over a range of fabric layers between six and ten layers and energy levels between 6.0 and 9.0 Joule. Fabric P61 with a mass per unit area of 61 g/m² is a very thin and light fabric. Due to this, it is clear, that stab depth tests lead to bad values. The impact energy of 9.0 Joule leads to dangerous injuries due to the fact, that stab depths between 49.3 and 52.0 mm are reached. Within a test series a decrease in stab depths can be recognized, but in fact, there are no significant differences between the panels of seven and eight layers visible. The nine and ten layer panels also show comparable results. In general it can be said, that a higher amount of layers lead to better results, but the addition of only one layer often does not show an effect.

2.4.1.2 Pattern P170

The mean values of the stab depth of plain pattern P170 is presented in Table 2-5. The stab depth measurements for the respective multi-layer panel also show an increase in stab depth values at higher impact energies.

Table 2-5: Mean stab depth results for P170

Energy	6 layers	7 layers	8 layers	9 layers	10 layers
4.5 Joule	19.3	18.7	14.0	12.7	13.3
6.0 Joule	34.3	32.7	27.7	27.3	24.7
7.5 Joule	42.7	39.0	36.3	36.0	34.0
9.0 Joule	44.3	43.7	42.3	40.3	42.7

The results of the different number of layers of the plain weave fabric P170 are presented in Figure 2-13.

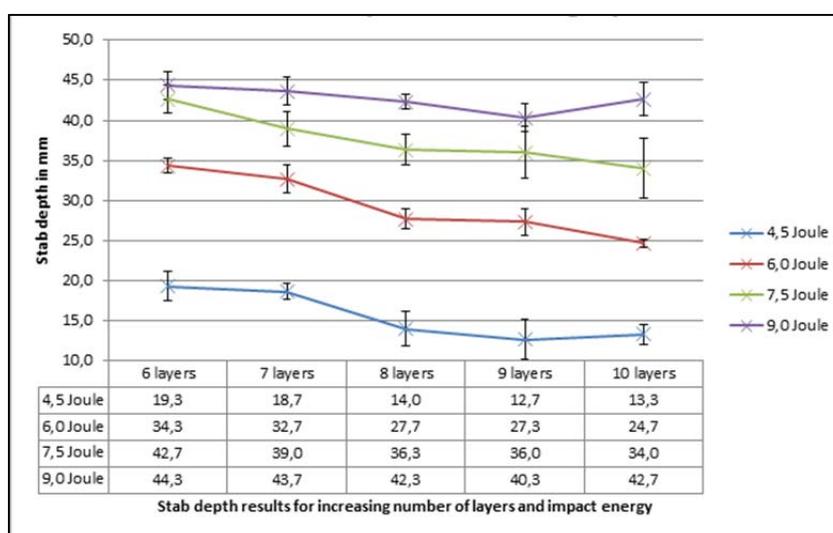


Figure 2-13: P170 - Stab depth of increasing layers

The plain weave P170 shows another effect. The values show a jump at eight layers whereas six and seven layers are comparable. The panels between eight and ten layers show similar results, due to the high variation between the values. An impact energy of 9.0 Joule shows no significant differences between six and up to ten layers.

2.4.1.3 Pattern P230:

The pattern P230 is the last plain weave pattern in this series. It is the thickest and heaviest plain weave pattern with a mass per unit area of 230 grams per square meter. The differences between the impacts do not seem to be as strong as the other plain weave pattern. This is especially visible in the differences of the impact energy of 6.0 Joule up to 9.0 Joule.

Table 2-6: Mean stab depth results for P230

Energy	6 layers	7 layers	8 layers	9 layers	10 layers
4.5 Joule	18.0	16.3	14.7	14.7	13.7
6.0 Joule	31.3	28.7	24.3	24.3	21.0
7.5 Joule	33.7	33.7	31.7	30.7	30.3
9.0 Joule	39.3	36.3	36.0	35.0	31.0

It can be seen that the stab depths increases with higher impact energies.

The stab depth measurements of the plain weave fabric P230 are presented in Figure 2-14.

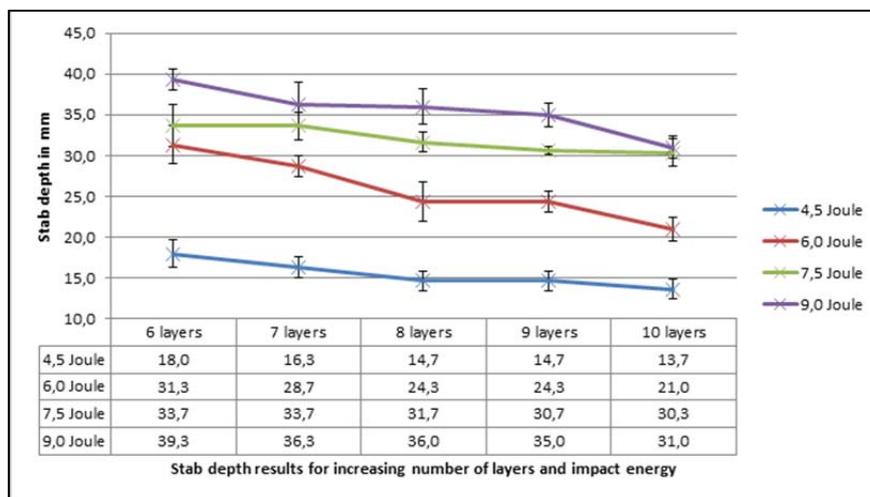


Figure 2-14: P230 - Stab depth of increasing layers

The plain weave fabric P230 shows a decrease in stab depth results by additional layers but also by increasing the impact energy. The biggest difference in the results shows the series made at an impact of 6.0 Joule, where values between 31.3 mm for 6 layers of fabric and 21.0 mm for 10 layers of fabric are measured. The other curves are flatter, which means, that they are showing minor differences within the results. The influence of the number of layers is very low, if just one layer is added. That is the reason why in practice soft body armour panels consist of up to 35-40 layers.

2.4.1.4 Pattern T170

The stab depth measurements for the respective multi-layer panel of twill pattern T170 show an increase in stab depth values at higher impact energies. Also the twill pattern T170 shows the same behaviour as the other test series. An increase in the impact energy values results in

higher stab depth values. Table 2-7 gives an overview of the mean stab depth values of this fabric.

Table 2-7: Mean stab depth results for T170

Energy	6 layers	7 layers	8 layers	9 layers	10 layers
4.5 Joule	22.7	24.3	24.7	25.3	20.7
6.0 Joule	36.3	37.7	35.7	32.0	32.0
7.5 Joule	45.7	43.3	43.3	40.3	39.7
9.0 Joule	50.3	49.7	47.3	44.7	46.3

An analysis shows that the test series for nine layers show a different development of the values than the other curves.

The two different twill fabrics are also analysed due to differences between their impact behaviour with an increasing number of layers.

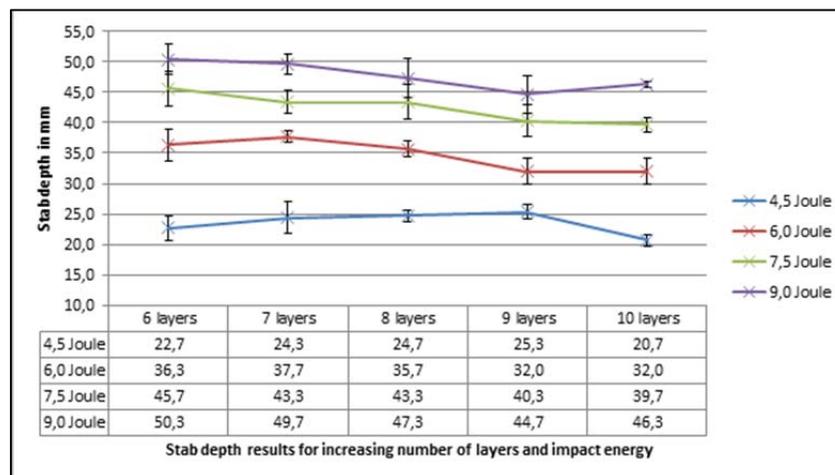


Figure 2-15: T170 - Stab depth of increasing layers

The twill weave pattern T170 does not show a decrease in stab depth values in general. The values vary in both directions, so that no general statement about the influence of the number of layers can be made for the twill pattern T170. To achieve meaningful results of the effect of the number of layers, in order to draw conclusions about the effect of the number of layers, test series with more layers at higher impact values have to be done.

2.4.1.5 Pattern T230

In between the impact energies, the different numbers of layers show no significant differences between the results. It seems that the stab depth values at an impact of 4.5 Joule are much lower than the other series. The values for an impact of 6.0 Joule are twice as high as the impact energy of 4.5 Joule. After that, the values increase less than 10 mm per series.

Table 2-8: Mean stab depth results for T230

Energy	6 layers	7 layers	8 layers	9 layers	10 layers
4.5 Joule	14.7	15.7	13.0	14.7	14.7
6.0 Joule	37.3	34.3	36.3	33.3	36.3
7.5 Joule	43.7	45.3	41.7	38.7	40.7
9.0 Joule	52.3	52.0	50.3	50.0	48.7

The twill weave fabric T230 is the heaviest twill fabric and has a loose structure. In total the stab depth values of the twill weave fabrics are much higher than the plain weave fabrics.

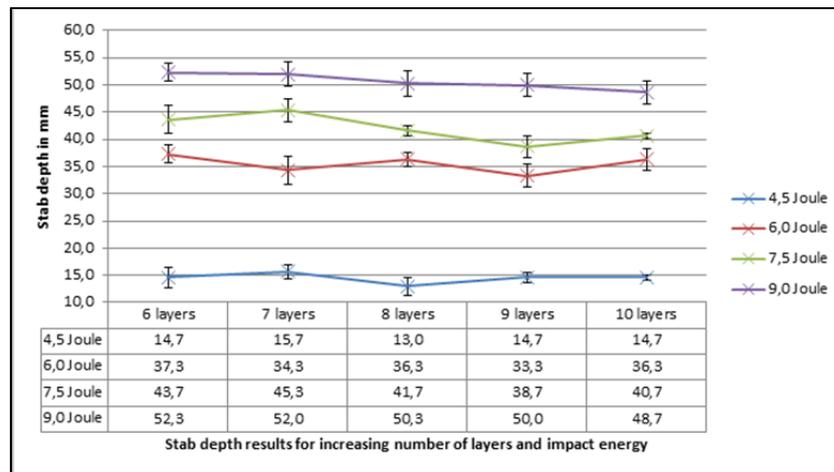


Figure 2-16: T230 - Stab depth of increasing layers

The test series for the impact energies of 4.5 Joule and 9.0 Joule show no differences in their results in between the panels with a different number of layers. Also the other two series vary in the results but give no conclusion about the effect of the number of layers. The results of the test series for the impact energy of 4.5 Joule are much lower than the other series.

2.4.1.6 Conclusion

An analysis between the impact energies and the stab depth show an increasing of the stab depths at higher impact energies for all fabrics. A doubling of energy impacts leads to twice

as deep stab depths. It is assumed, that predictions of the stab depth at higher impacts can be taken out of this analysis.

For all different fabric types it can be said, that the number of layers gives no significant trends of stab depths. It is assumed, that the number of layers is not high enough to find out the differences, because in practice, panels out of 35-40 layers are taken to give a sufficient protection against injuries caused by a stab attack.

2.4.2 Relation between structure parameters and puncture resistance

A further study was carried out to assess a wider variety of structure parameters of the materials. After Potluri and Needham (Scott 2005)) the type of surface structure has a significant effect on the physical and mechanical properties of fabrics. To see such an influence of the design features of the stab resistance of various aramid fabrics, the measured penetration depths are analysed separately according to different criteria such as the mass per unit area and the pattern. The aim of this series was to establish the penetration characteristics of different armour materials with the main variables pattern, mass per unit area and thickness of the fabrics. The energy impacts of 6 Joule and 9 Joule were chosen to find out the differences between the parameters. Tests were carried out with panels out of six and up to ten layers of aramid fabrics. The five different fabrics, like presented in the previous chapters are analysed regarding the relationship between the structure parameters and the stab depth.

2.4.2.1 Comparison of plain weave structures

An initial assessment of the different aramid fabrics shows that the individual fabrics allow very different penetration depths of the blade. The plain fabric P230 presents the significantly best result, while the fabric P61 is able to have the smallest stab inhibition. Moreover, a relatively identical behaviour during the stabbing process can be noticed for the heavier fabrics. Only partly individual filaments are cut in all fabrics. Furthermore a mechanism of thread displacement is seen, where the blade causes larger holes, which can be traced back. Only the thin fabric P61 is cut completely by the blade.

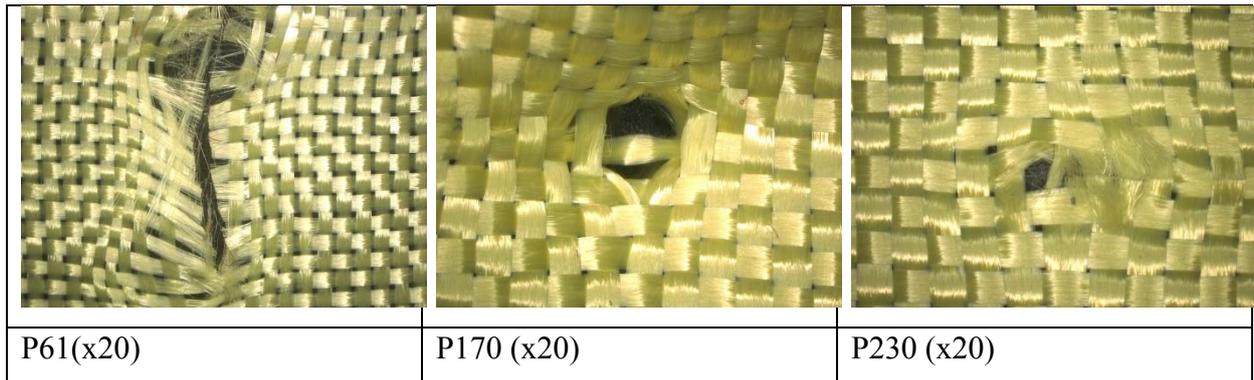


Figure 2-17: Optical observation after the stab impact at 20x magnification

Figure 2-18 presents the stab depths of the three different plain weave structures for an impact of 6.0 Joule.

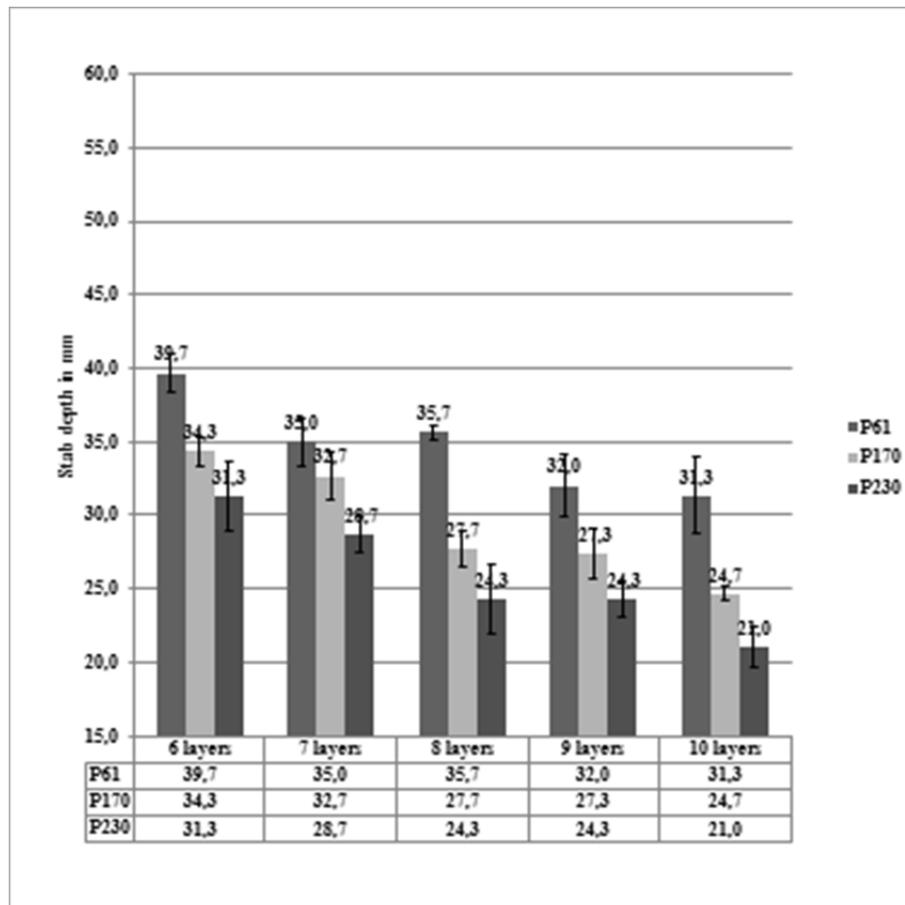


Figure 2-18: Comparison of plain weave samples at 6 Joule impact

It is presented that the stab depth decreases by increasing of the mass per unit area. The very thin fabric P61 shows significantly higher stab depth impacts than the other fabrics. The plain weave P170 allows deeper punctures of an average of 3 mm than the P230. By increasing the

impact energy from 3.0 Joule to 9.0 Joule, the following results can be seen as figure 2-19 shows:

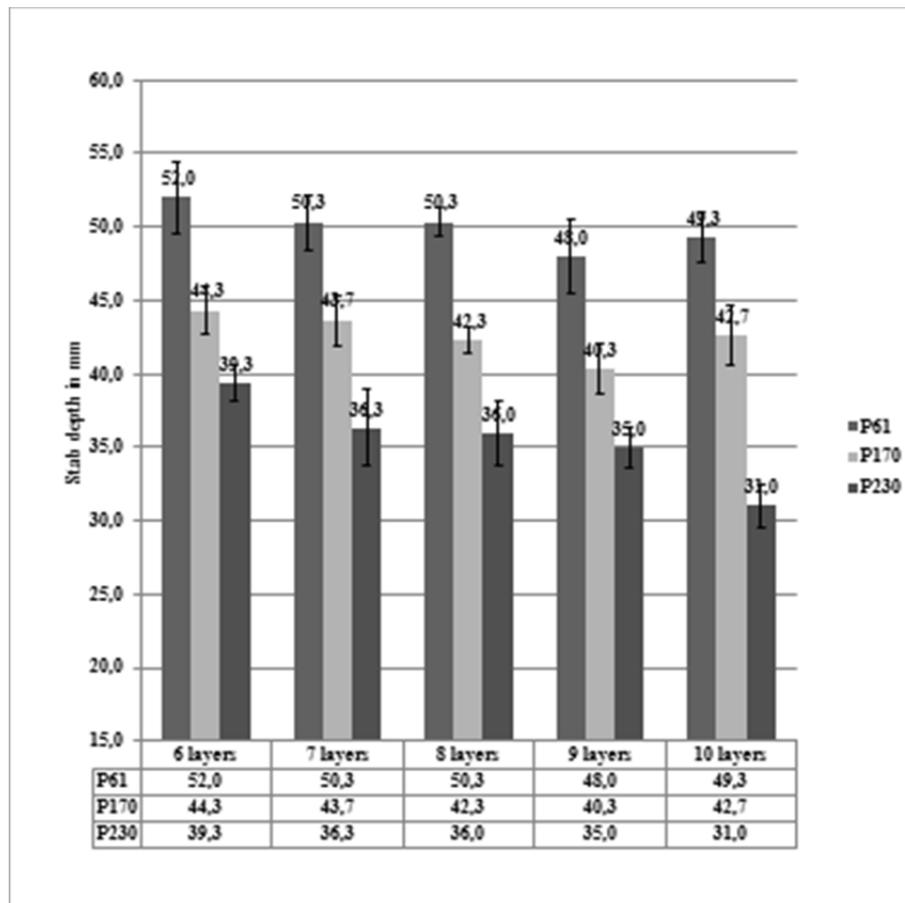


Figure 2-19: Comparison of plain weave samples at 9 Joule impact

The distance of stab depths between the fabrics increases by raising the impact energies. The P61 fabric reaches values of about 50 mm depths for all layer panels, while the values for the P230 present values between 31.0 mm depth for 10 layers and 39.3 mm for 6 layers. The P170 fabric presents values between 42.7 mm and 44.3 mm. The distances between the panels do not seem to be significant.

2.4.2.2 Comparison of twill weave pattern

In the following the penetration of the twill fabrics are compared, to evaluate the influence of the construction parameters such as mass per unit area and thickness of the fabrics. T170 presents a 170 g/m² fabric with a thickness of 0.27 mm and T230 is a 230 g/m² fabric with a 0.36 mm thickness. Interestingly, the two twill fabrics show similar results, so that depending on the number of layers sometimes the lighter performs better, sometimes the heavier and thicker twill fabric. At an impact energy of 6.0 Joule the T170 mostly shows the better result,

while the T230 has a better performance at an impact of 7.0 Joule. Also here an identical behaviour during the stabbing process can be noticed for both fabrics. Only partly individual filaments are cut in all fabrics. Again, the thread mechanisms of displacement is seen, where the blade causes larger holes, which can be traced back.

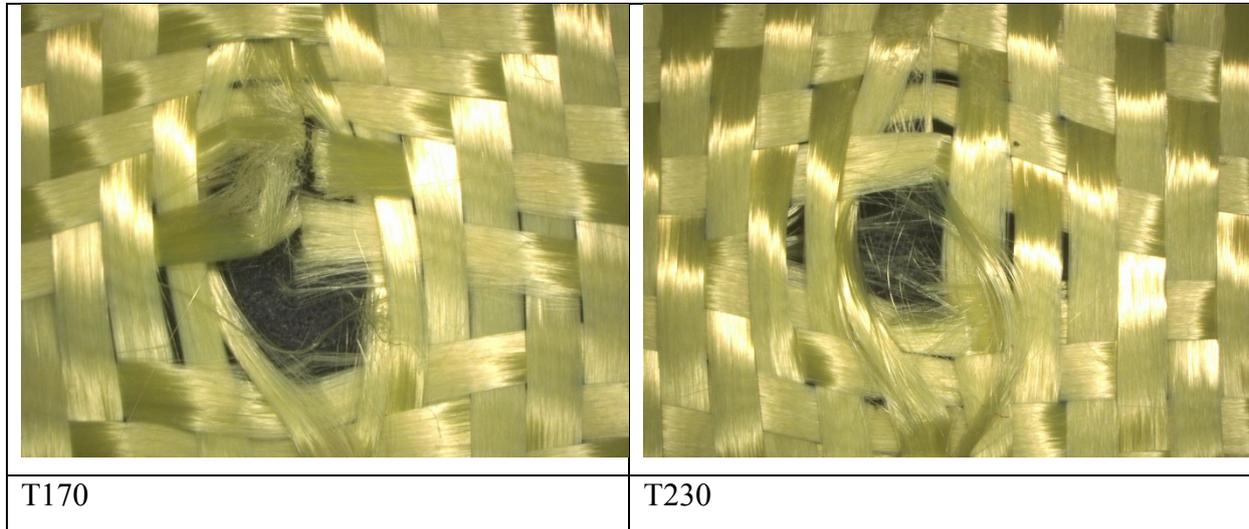


Figure 2-20: Optical observation after the stab at 20x magnification

The twill fabrics show more displacements due to the loose structure of the fabrics. The strongest degree of displacement can be determined at the twill fabric T170.

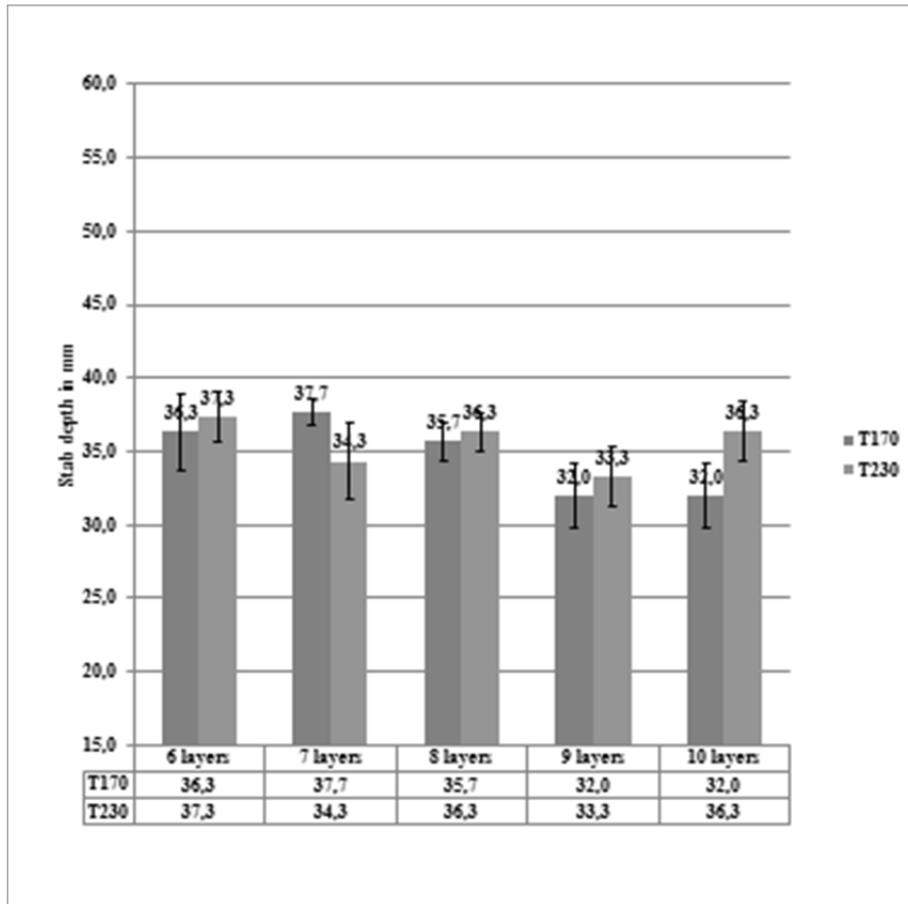


Figure 2-21: Comparison of twill weave samples at 6 Joule impact

Looking at the individual values, it can be seen that all the results are relatively close together. The minimum result presents the twill T170 with 32.0 mm for nine and ten layers and the maximum result is presented for the T170 with 37.7 mm for the seven layer panel. All other values are in between these values.

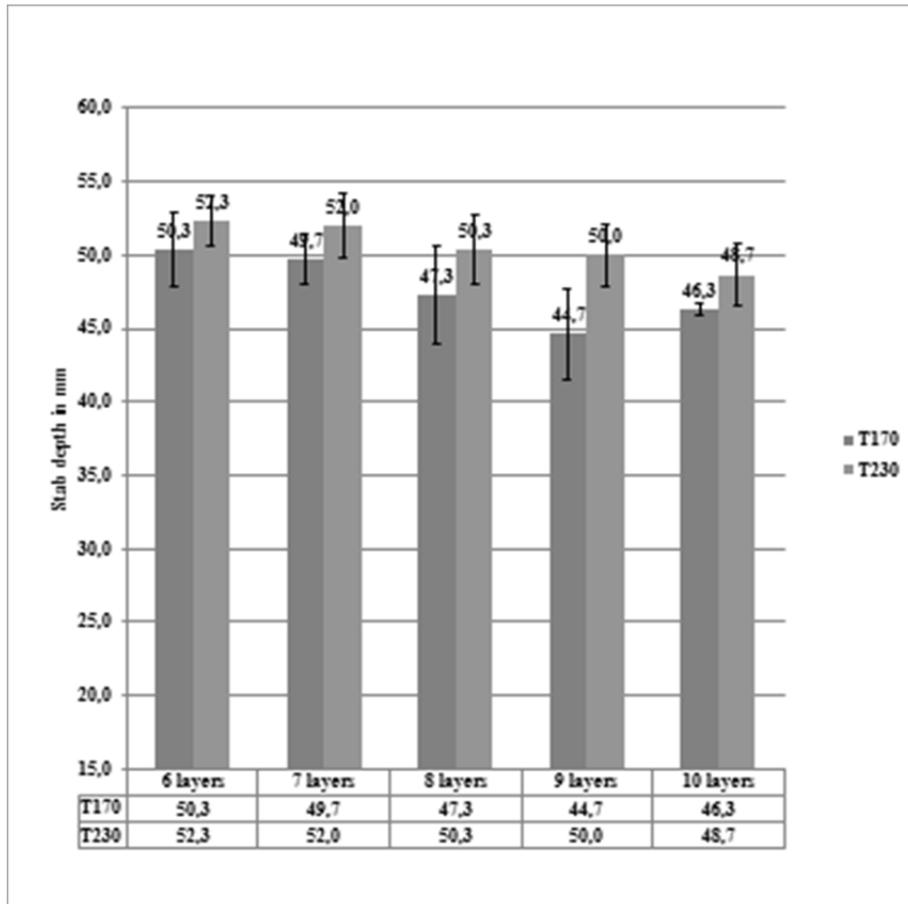


Figure 2-22: Comparison of twill weave samples at 9 Joule impact

The results of the test series at an impact of 9.0 Joule vary between 44.7 mm for a panel of 9 layers of the fabric T170 and 52.3 mm for a panel of 6 layers of the fabric 230. There is just a 7.5 mm range between all test series. Looking at the measured penetration depths it is found that the fabrics have a poor stitch inhibitory effect. They allow a relatively high penetration depth and also strong displacement effects in the puncture area of the blade.

2.4.2.3 Comparison plain vs. twill for two different mass per unit areas

In the next series of trials, the influence of pattern was analysed. The aim of this series was to establish the penetration characteristics of the different fabric types with the same mass per unit area weight. First, the fabrics P170 and T170 are compared, due to the fact, that they have the same mass per unit area with 170 g/m² but a plain and twill weave pattern. The presented type of fabrics show the general trend that the penetration depth of the blade with an increasing number of layers decreases, but with a different strong trend, like demonstrated in Figure 2-23.

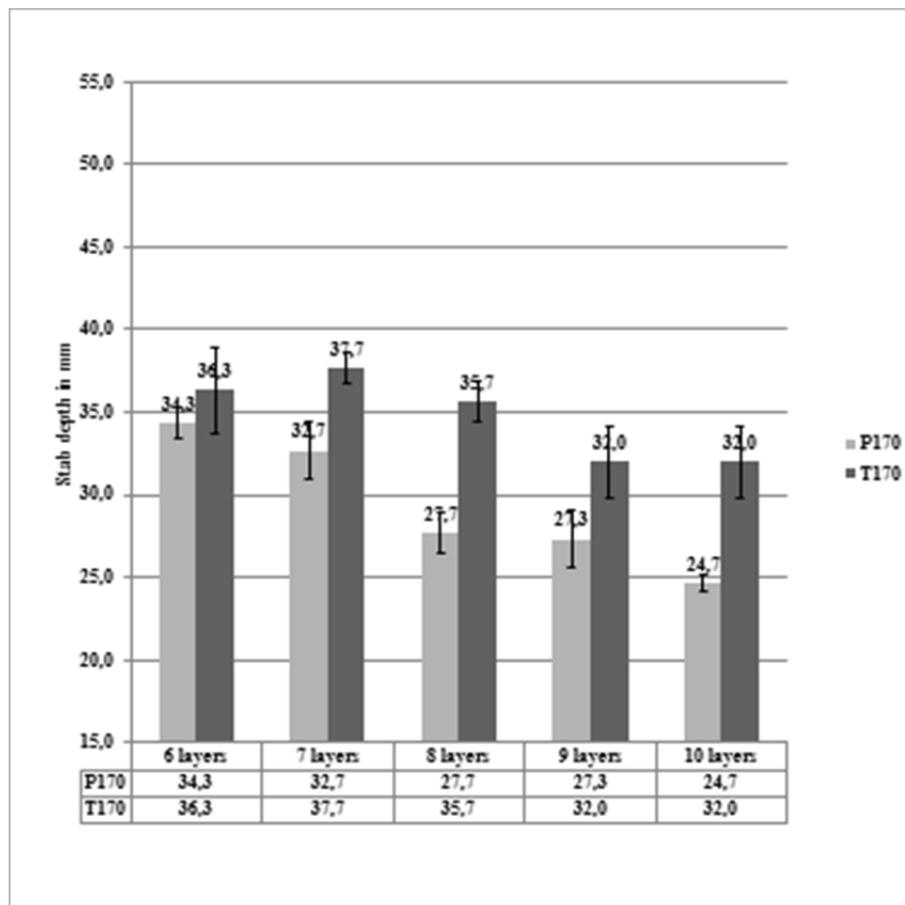


Figure 2-23: Comparison of plain weave vs. twill weave 170g/m² at 6 Joule

The stab depth of the plain weave fabric decreases from 34.3 mm for six layers to 24.7 mm for ten layers at an impact of 6.0 Joule. The twill weave fabric T170 is penetrated by 36.3 mm in a six-layer panel and decreases to 32.0 mm for ten layers, but the panels between six and eight layers give the same stab depth values. The plain weave pattern show better and lower stab depth values, but only between 2 mm for six layers and 7 mm for eight layers.

Also the two fabrics are compared at an impact energy of 9.0 Joule, to give additional information on the differences of the impact behaviour of the different pattern.

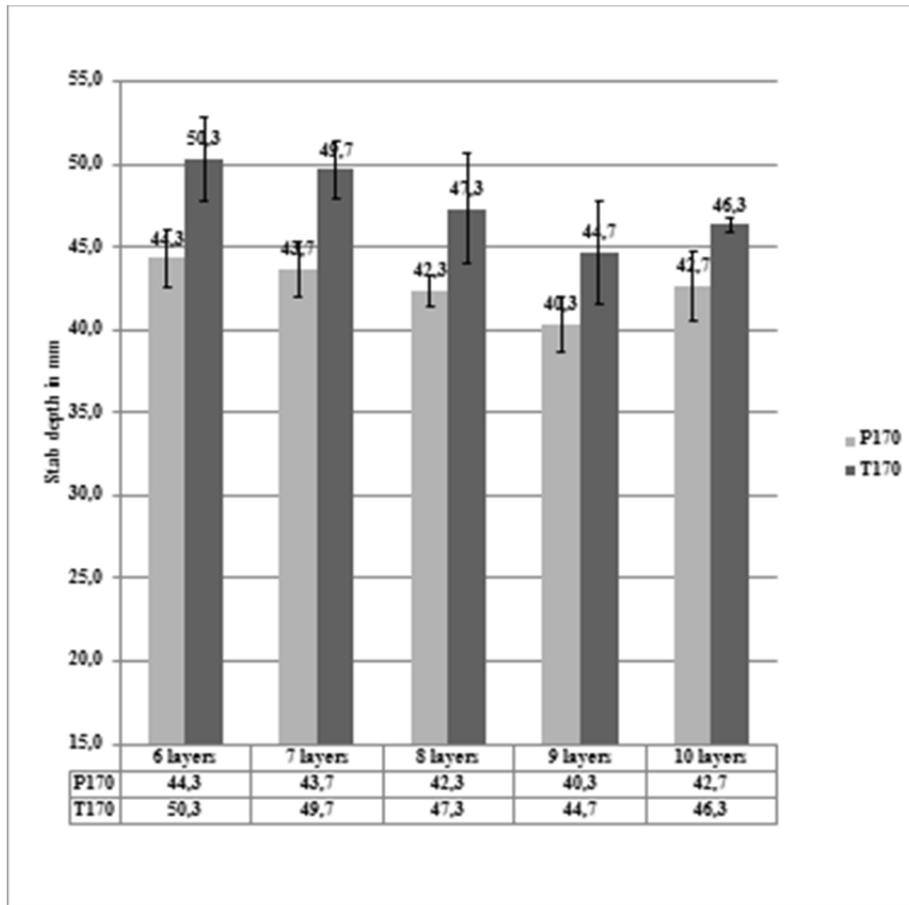


Figure 2-24: Comparison of plain weave vs. twill weave 170g/m² at 9 Joule

The stab depth of the plain weave fabric decreases from 44.3 mm for six layers to 42.7 mm for ten layers at an impact of 9.0 Joule. The twill weave fabric T170 is penetrated with 50.5 mm in a six-layer panel and decreases to 46.3 mm for ten layers, but the panels between six and eight layers give the same stab depth values. The plain weave pattern gives better and lower stab depth values of about 5 mm in mean.

Not only were the lighter fabrics with a weight of 170 g /m² compared, but also the heavier fabrics with 230 g /m². They are presented in the following figures. Again a comparison was made at two impact energies. First they were compared at an impact of 6.0 Joule. These two samples have identical thread counts and fineness but differ in their pattern and also in the fabric thickness.

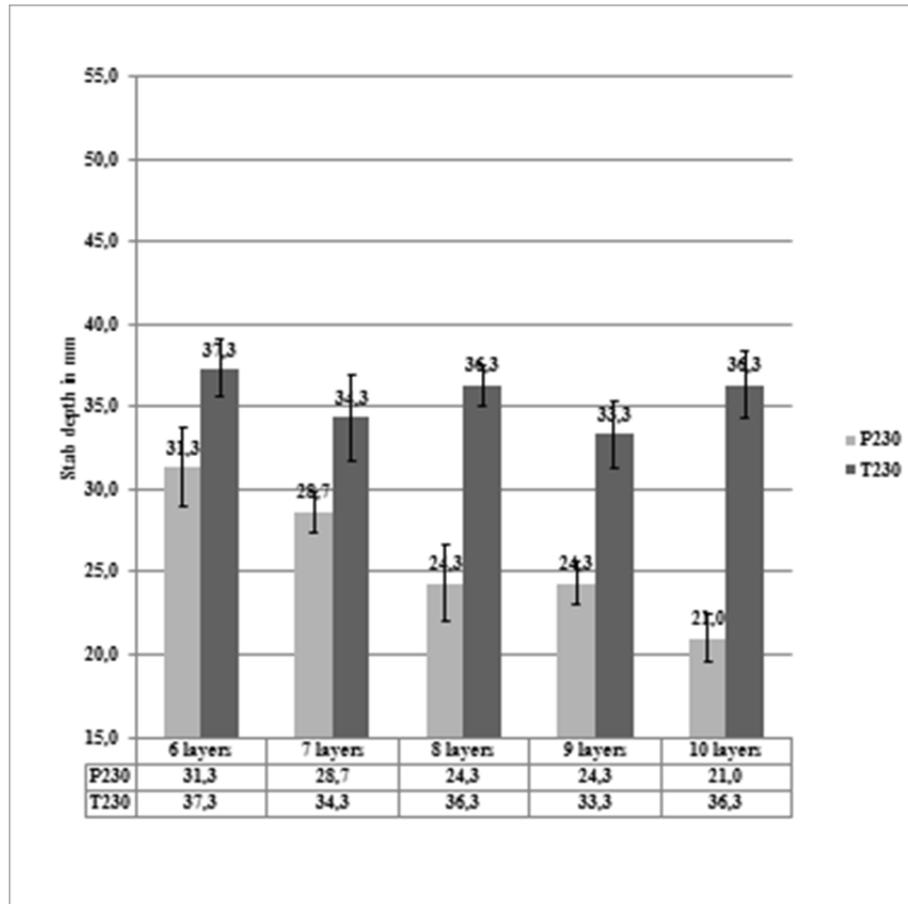


Figure 2-25: Comparison of plain weave vs. twill weave 230g/m² at 6 Joule

Again, a decreasing trend in the depth of penetration with an increasing number of layers can be seen for the plain weave fabric, but the twill weave fabric shows variations in nearly the same results. In comparison, the plain weave fabric shows significantly better results. The panels between eight and ten layers show differences of more than 10 mm depth, while the panels with less layers show differences of just 5.7 mm for seven layers and 6.3 mm for six layers. Analysing the same fabrics at a higher impact energy of 9.0 Joule, the following results are determined:

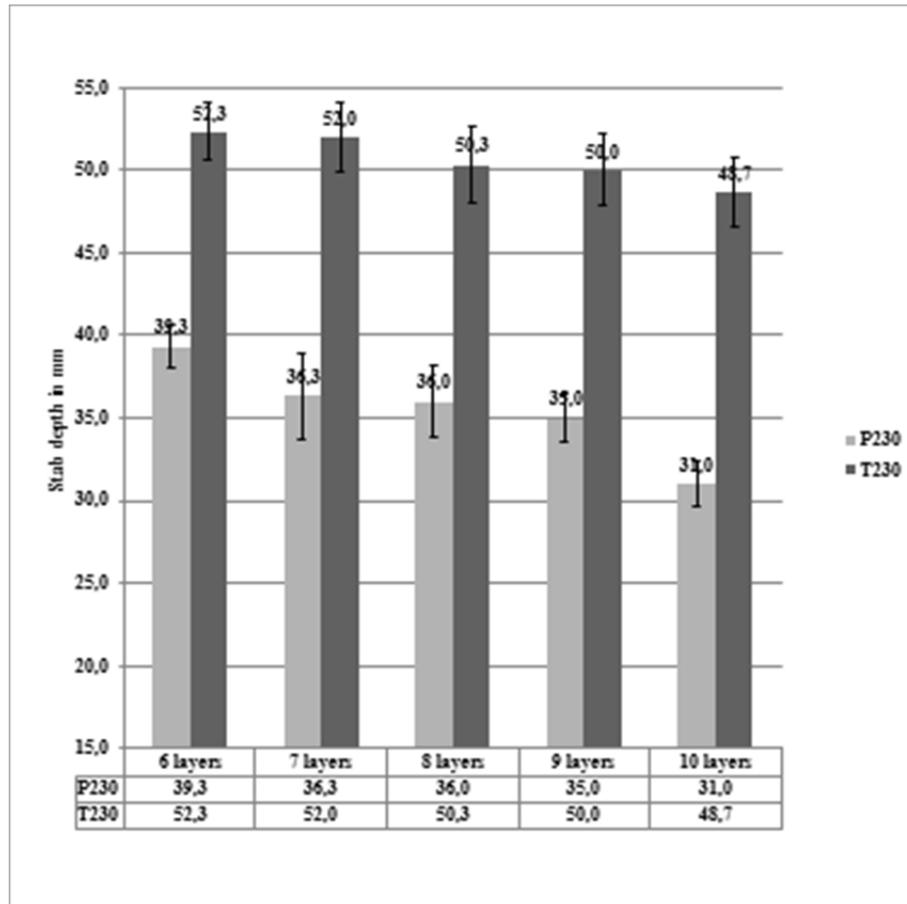


Figure 2-26: Comparison of plain weave vs. twill weave 230g/m² at 9 Joule

A comparison of the plain and the twill pattern shows that all panels have stab depth differences of about 15 mm between the patterns. The plain weave pattern is much better than the twill weave pattern, which confirms the assumption that the loose structure of the twill fabric leads to a sliding apart of the yarns and the knife can penetrate the layers easier.

2.4.2.4 Conclusions

Based on the performed tests it can be assumed that the construction parameters of aramid fabrics present a significant influence on the stab inhibitory effect. The individual fabric types allow very different penetration depths of the blade. All three plain weave structures show a better application possibility than the twill pattern. The heavier the fabric, the better the stab resistance. The two different twills do not greatly show affects in the stitch inhibition from the measured penetration depth.

2.5 Parameters, which influence the stab resistance of woven fabrics

In the production of body armour panels, multilayer aramid fabrics are normally used. A main problem of these panels is the high weight and consequential lower comfort for the wearer, like mentioned before. To reduce layers with a concomitance of the same safety standards, the panel has to be improved (Reiners 2014). Due to the smoothness of para-aramid yarns, the friction between the yarns and fabric layers is often too low; in this case slippage occurs, which leads to lower impact against stabbing. In contrast to that, a higher friction between the yarns leads to a higher energy absorption, because the yarn sliding is restricted (Guo et al. 2014; Nilakantan, Gillespie 2013).

In the following, the property of friction and other properties, which influence the yarn migration, will be analysed and compared, to define how to measure the slippage of the yarns but also the frictional behaviour.

2.5.1 Textile friction

The aim of this series was to find out interdependencies between the frictional characteristics of different armour materials and the stabbing performance. Four aramid fabrics, which were explained in detail before, were tested. They were chosen, in order to compare similar structures. Two plain weaves with 170 g/m² and 230 g/m² and two twill weaves with 170 g/m² and 230 g/m² were compared in order to analyse the influences of the pattern of same mass per unit areas and also to compare different weight of similar patterns.

The static and dynamic coefficient of friction was determined according to the test standard for coated fabrics (Standard DIN EN 14882), which is also suitable for textile fabrics. Figure 2-27 shows the principle of testing. In this test a sled (6) is placed on a fabric (5), which is fixed free of tension on a horizontal surface (4). The sled is connected to a measuring device (1), which records the force. For these test series, a Statimat ME was used with a measurement head of 10 Newton. The sled is pulled by a free of tension yarn (2), which is lead through an idler pulley (3) over the sample with a test speed of 100 mm/min, wherein the maximum force for starting the movement (static) and the continuing constant speed over a measurement distance of 50 mm (kinetic) is measured.

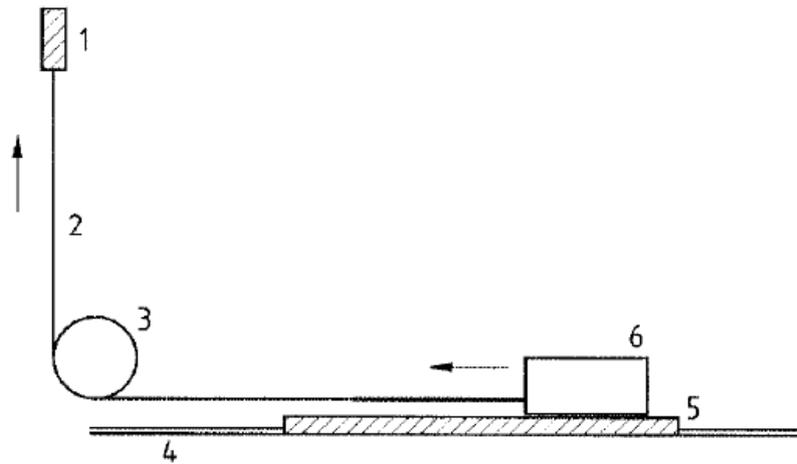


Figure 2-27: Principle of friction measurement

The coefficient of static friction and kinetic friction are calculated by the following formulas:

$$\mu_s = \frac{F_s}{W} \quad (16)$$

with the static coefficient of friction μ_s with the mean force F_s and the weight of the sled W and

$$\mu_k = \frac{F_k}{W} \quad (17)$$

for the kinetic coefficient of friction μ_k with the mean force F_k and the weight of the sled W .

To determine the influence of the fabric type, tests were carried out fabric against fabric in warp and weft direction. Therefore the fabric with a size of 80x41 mm was stuck on the metal sled with double-sided tape and at the front raised three mm to avoid additional friction influences, like presented in Figure 2-28.



Figure 2-28: Fixed fabric on the sled

The sled has a weight of 240 grams and is put onto the fabric on the bottom. After a time of five seconds the measurement starts. Therefore the sled is pulled around the pulley, like Figure 2-29 presents. The static and kinetic forces are measured to pull the sled over the fabric on the bottom.



Figure 2-29: Friction measurement device

The first fabric direction presents always the fabric on the bottom and the second fabric is the fixed fabric on the sled.

2.5.1.1 Results

Three tests of each fabric are carried out and the mean values are presented. First, the influence of the test direction is analysed for each fabric type. Afterwards the kinetic and static friction forces between the different fabrics are compared. One main goal of this work was to find out, if wool, takes a positive influence onto the frictional behaviour of smooth aramid fabrics. Therefore the wool fabric is analysed too and afterwards the friction of the fabrics are compared to the friction of the fabrics against wool.

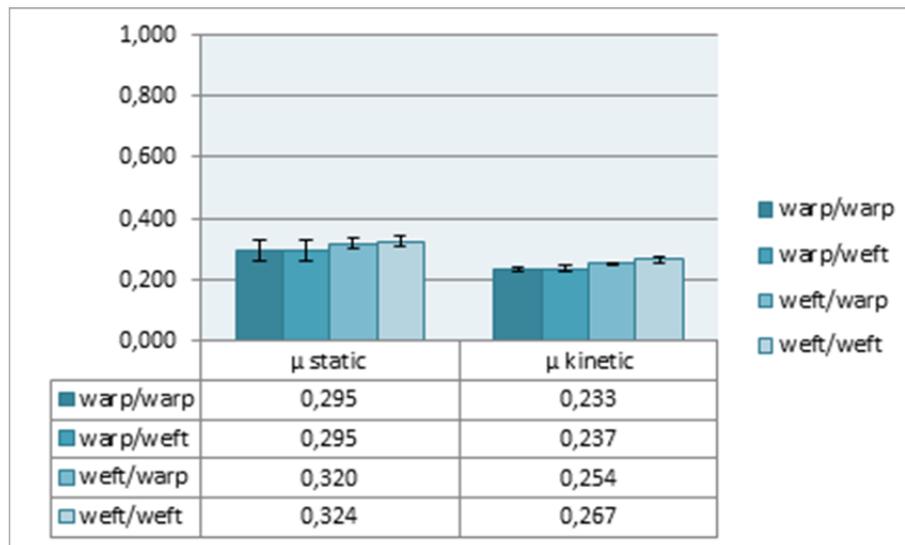


Figure 2-30: P61 Coefficient of friction

The static coefficient of friction is in all four direction combinations comparable. The results are between 0.295 and 0.324. The kinetic coefficients are comparable for the fabrics, where the bottom fabric shows the same direction. The warp against warp and warp against weft present results of 0.233 and 0.237, which are similar and the two weft direction fabrics have values of 0.254 and 0.267, which are higher than the results in warp directions.

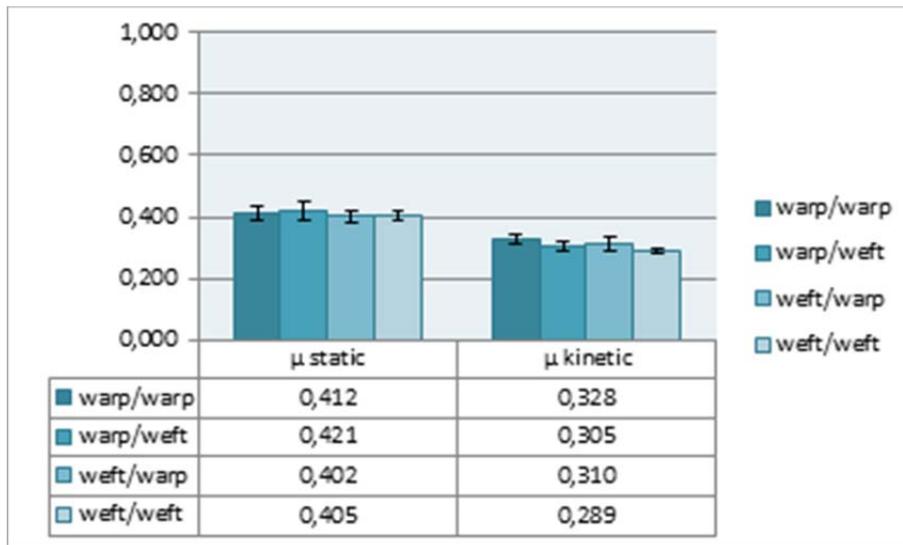


Figure 2-31: P170 Coefficient of friction

The plain weave P170 fabrics show again comparable results for the static friction coefficient with values between 0.402 and 0.421. The kinetic friction presents the highest result for the fabric combination warp/warp with $\mu = 0.328$. But nevertheless the results are similar.

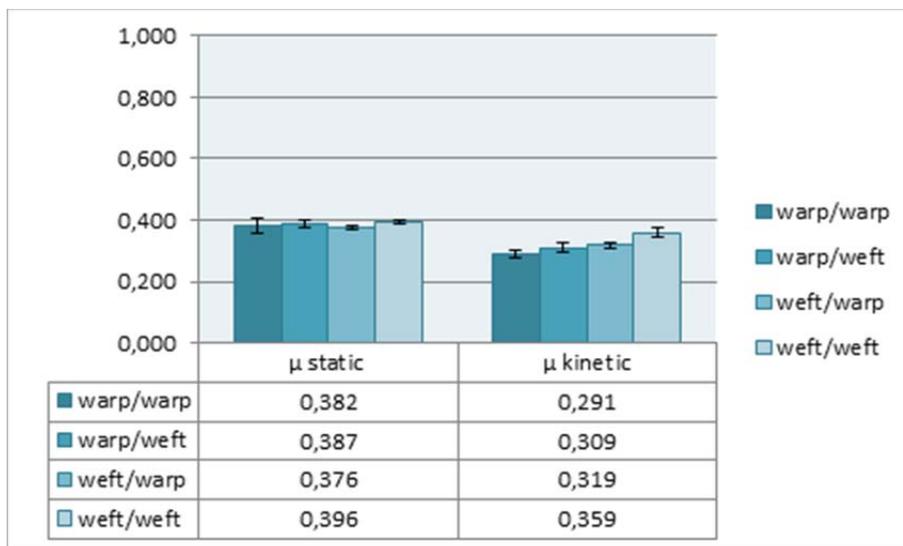


Figure 2-32: P230 Coefficient of friction

The thickest and heaviest plain fabric P230 gives comparable results for the static friction coefficient between 0.379 and 0.396. The kinetic coefficients are increasing from warp to weft directions with values from 0.291 to 0.359.

The results obtained for twill fabrics are presented in Figure 2-33 (170 g/m²) and Figure 2-34 (230 g/m²). Figure 2-33 shows the results for the twill fabric T170.

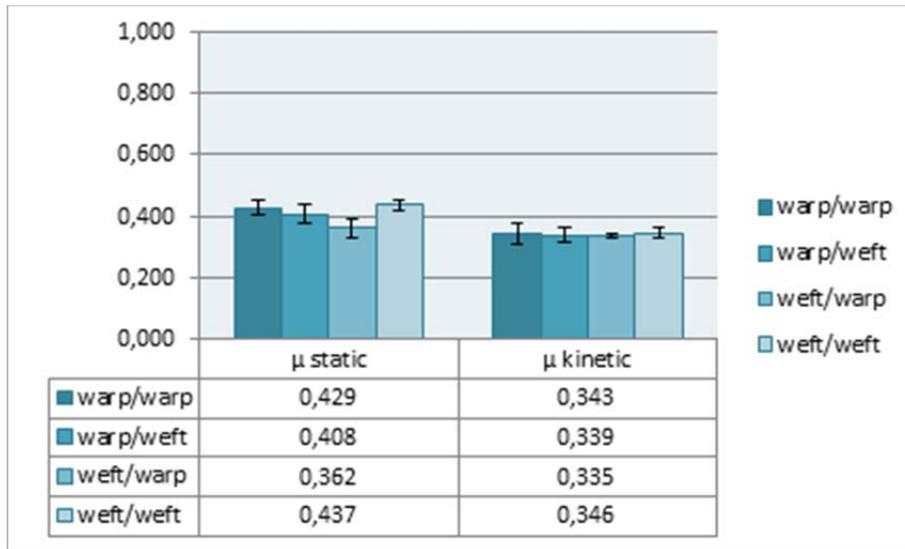


Figure 2-33: T170 Coefficient of friction

While the kinetic results for the coefficient of friction are comparable and show results between 0.335 and 0.346, the static friction results vary. The weft/warp direction presents the lowest friction resistance with a value of 0.362, while the other results are higher with values between 0.408 and 0.429.

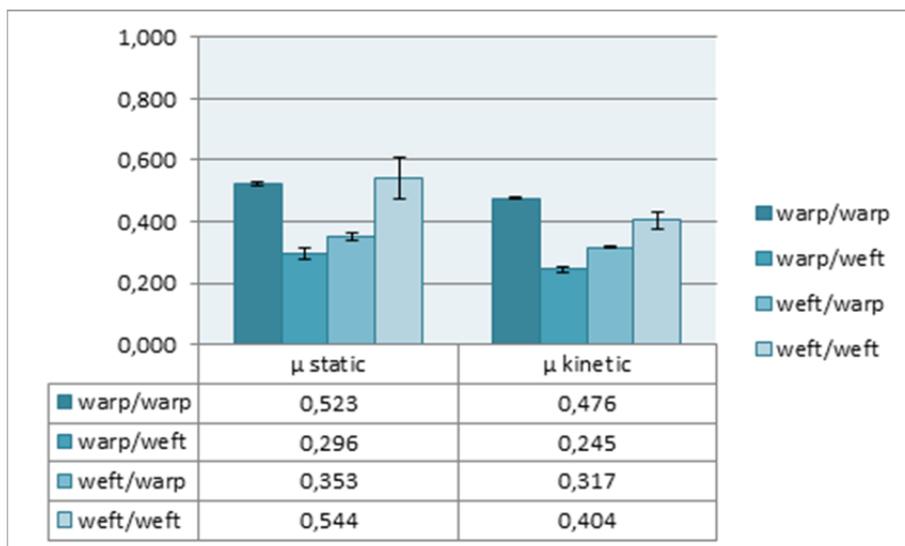


Figure 2-34: T230 Coefficient of friction

The results of the last twill pattern T230 give other results than the tested fabrics before. The highest values of the static friction can be seen for the warp/warp and weft/weft directions

with values of 0.523 and 0.544. Also the kinetic friction coefficients show these tendencies with values of 0.476 and 0.404, while the values in between are 0.296 and 0.353 for the static friction of warp/weft and weft/warp and 0.245 and 0.317 for the kinetic friction coefficients of these combinations.

To compare the frictional behaviour of aramid fabrics with other materials, also the plain weave wool, which was also used in previous test series, was tested. Results are presented in Figure 2-35.

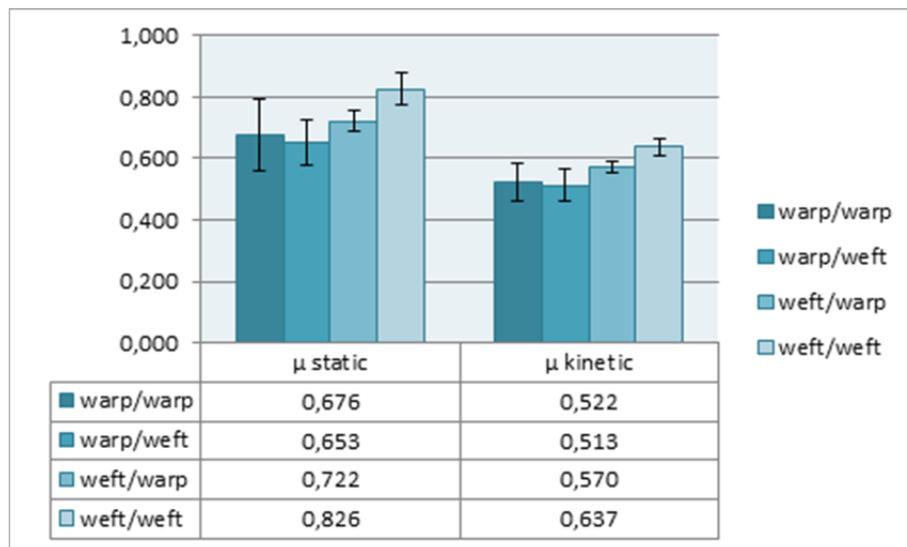


Figure 2-35: Wool Coefficient of friction

The weft directions show higher tendencies of friction coefficients than the warp directions for both series.

As previously explained, it is assumed that denser fabrics having finer threads and more threads per cm show a lower resistance against friction, since the up and down of the warp threads are reduced and thus the fabric has a more even surface. Also the kind of fibre material influences the frictional behaviour (Arshi et al. 2012). Following the results of the different aramid fabrics and the wool fabric are compared with each other. The static and kinetic coefficients of friction are compared for all combinations of warp and weft directions. Results of warp/warp are presented in Figure 2-36; warp/weft results are presented in Figure 2-37, weft/warp results in Figure 2-38 and the weft/weft results are presented in Figure 2-39.

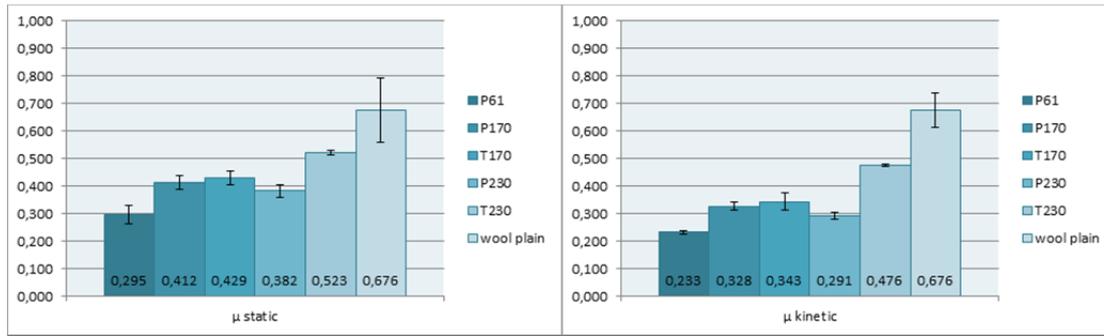


Figure 2-36: Static and kinetic friction warp/warp

The plain weave fabric P61 has the lowest result with a friction coefficient of 0.295 for static and 0.233 for kinetic friction. The two fabrics with a mass per unit area 170 g/m² show comparable results with friction coefficients of 0.412 and 0.429 for the static friction and 0.328 and 0.343 for the kinetic friction, while the P230 has lower values with 0.382 for static friction and 0.291 for kinetic friction. The T230 presents the highest values with 0.523 and 0.476, but still much lower than the wool values.

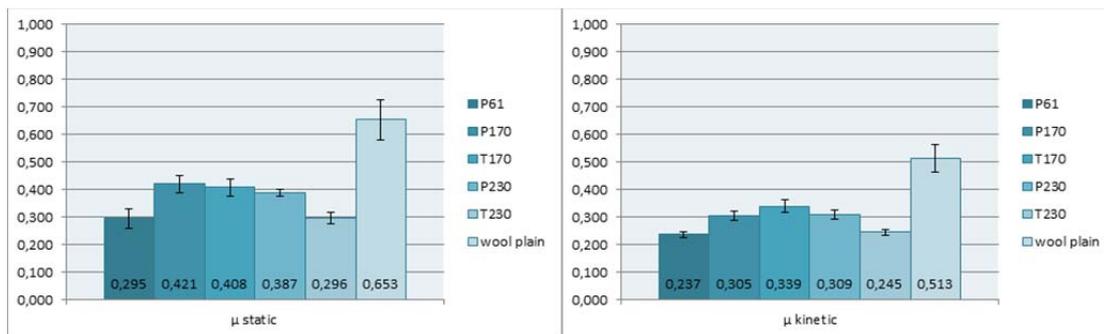


Figure 2-37: Static and kinetic friction warp/weft

The combination warp/weft gives comparable results for P61 and T230 with relative low values of 0.295 and 0.296, which is in comparison with the wool fabric only half as large. The P170, T170 and P230 are comparable, too.

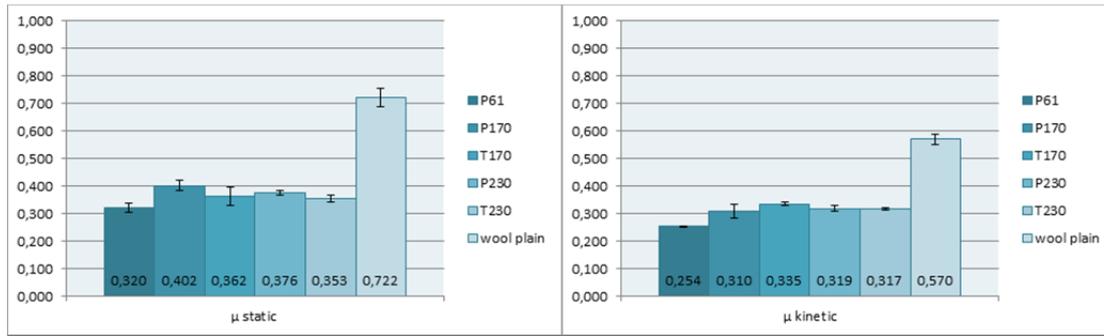


Figure 2-38: Static and kinetic friction weft/warp

The coefficient of friction of the fabric P61 is smaller than the values for the other fabrics. The fabrics P170 and T170 are comparable and also the fabrics P230 and T230. All four fabrics show similar results but they are significant smaller than the coefficient of friction of the wool fabric.

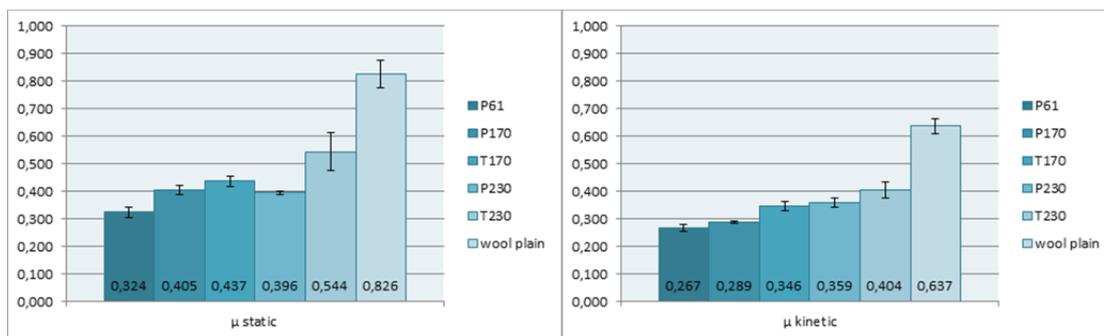


Figure 2-39: Static and kinetic friction weft/weft

From these results, it can be obtained, that the wool surface presents a significant higher coefficient of friction than the smooth aramid fabrics. It is assumed, that the surface of the wool gives a positive effect on the sliding apart threads of aramid because of its scaled structure. The scales can hook into the aramid threads and keep them at their place. To continue this adoption to pursue, a series of friction tests is performed in which the surfaces of the aramid fabrics are tested against the surface of the wool to see if there is a positive effect on the friction behaviour of the aramid fabrics.

To see directly the influence of the wool, a further analysis has been done. Therefore not the coefficients themselves are plotted to the diagrams, but the differences between aramids against aramids and aramids against wool for all combinations of direction. The higher the values the higher the influence of the wool to the frictional behaviour of the aramid surfaces.

On both axes, the coefficient of friction, μ is plotted in order to make the size of the friction coefficient differences visible. Comparing warp/warp of pure aramid with the warp/warp combination of aramid with wool for fabric P61, here the highest difference with μ of 0.09 is visible, and thus the greatest influence of wool on the aramid, like Figure 2-40 presents.

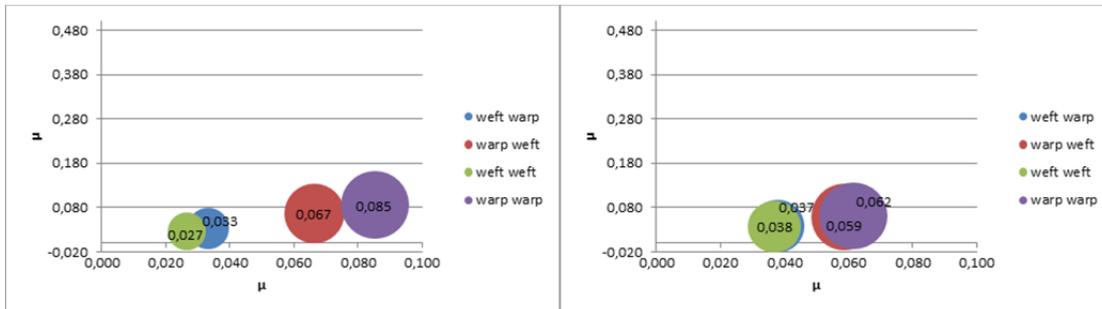


Figure 2-40: P61 Comparison with wool – static and kinetic

Also the warp/weft combination gives a high difference with $\mu = 0.07$, while the weft/warp directions show lower results for the static and kinetic friction results with values of 0.03 for static and 0.04 for kinetic friction coefficients. Figure 2-41 present the results for the P170.

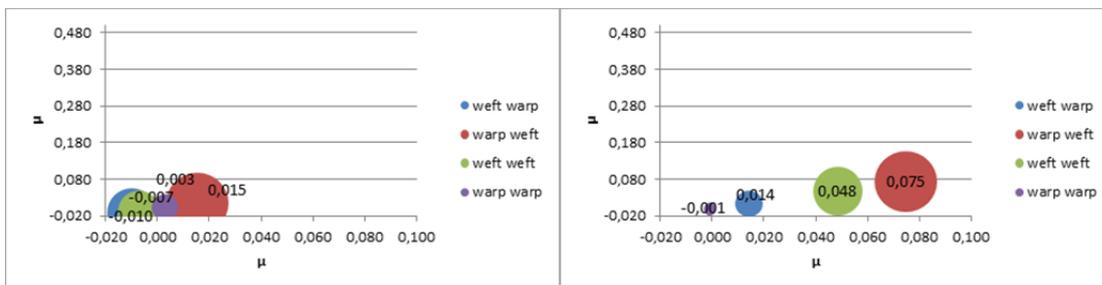


Figure 2-41: P170 Comparison with wool – static and kinetic

Again, the warp/weft and the warp/warp combinations show the highest results for the static friction, while the weft directions show no influences of the wool onto the frictional behaviour. The kinetic friction shows other results, here the warp/weft and the weft/weft combination show the highest differences, while the warp/warp show no influence of the wool and the weft/warp just a minimum influence of $\mu = 0.014$. The kinetic coefficient values are higher than the results for the static friction differences.

The P230 (Figure 2-42) presents the highest impact of the wool for the combinations with the weft fabrics on the bottom.

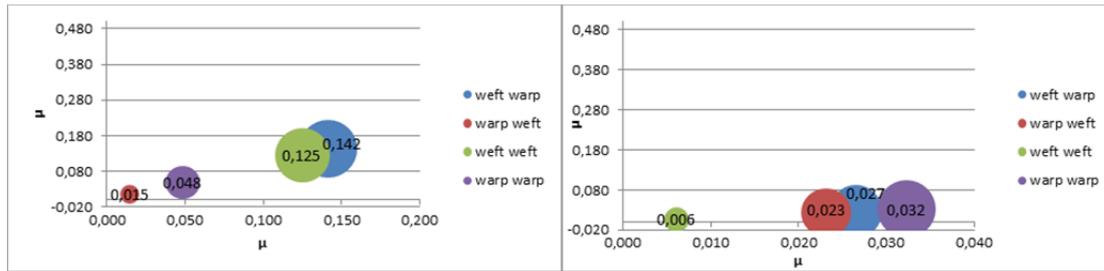


Figure 2-42: P230 Comparison with wool – static and kinetic

They show values of 0.125 and 0.142, while the combination warp/warp just has a value of 0.048 and the warp/weft series a value of 0.015. The kinetic test series show another behaviour. Here the weft/weft combination has a value of just 0.006, while the other series show results between 0.023 and 0.032. In total the influence of wool onto the static friction is higher than the influence onto the kinetic friction.

The twill fabric T170 (Figure 2-43) shows high values for the combinations warp/weft and weft/weft for the kinetic friction and the static friction. The values in total are very high, so it seems that the wool has a positive influence onto the surface of the aramid and the scales hook to the aramid threads.

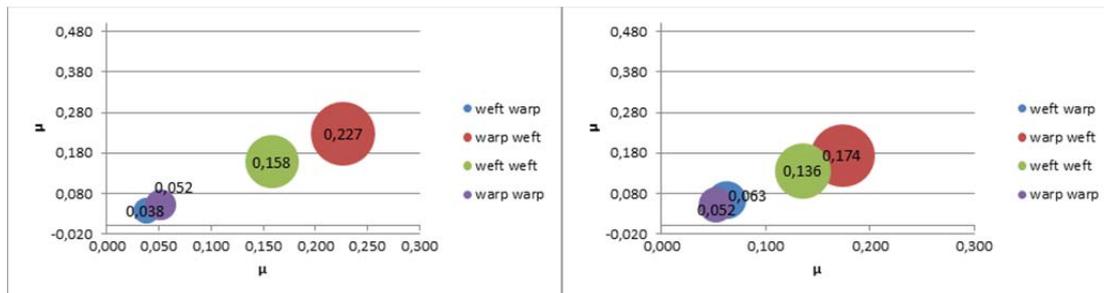


Figure 2-43: T170 Comparison with wool – static and kinetic

Figure 2-44 present the results of the twill fabric T230.

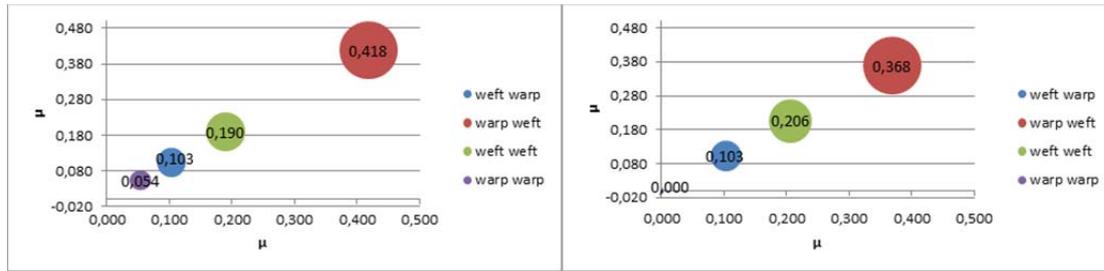


Figure 2-44:T230 Comparison with wool – static and kinetic

The behaviour is similar to the T170. The warp/weft and weft/weft combinations show the highest values, which are even higher than the values of the T170. The warp/weft combination has a static coefficient of friction of 0.418 and a kinetic coefficient of 0.368. The weft/weft combinations are nearly similar for static and kinetic with differences to pure aramid combinations of 0.190 and 0.206. In total it can be said, that the wool takes a great influence onto the friction behaviour of the aramid surface. While the plain pattern didn't show so high differences, the twill pattern presented high values.

To analyse the differences between the structures, the different pattern are compared, like presented in Figure 2-45 for the warp/warp combination. Again the difference in the friction coefficient between pure aramid and an aramid/wool combination was measured and plotted to the diagrams.

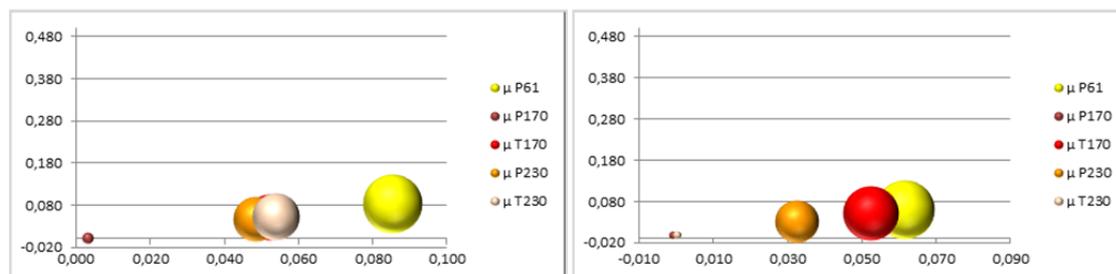


Figure 2-45: Static and kinetic friction - warp/warp

The warp/warp combination with the wool presents the highest influence onto the P61 fabric, the T170, P230 and T230 are comparable and the P170 show no influence through the wool fabric. The warp/weft combination is presented in Figure 2-46.

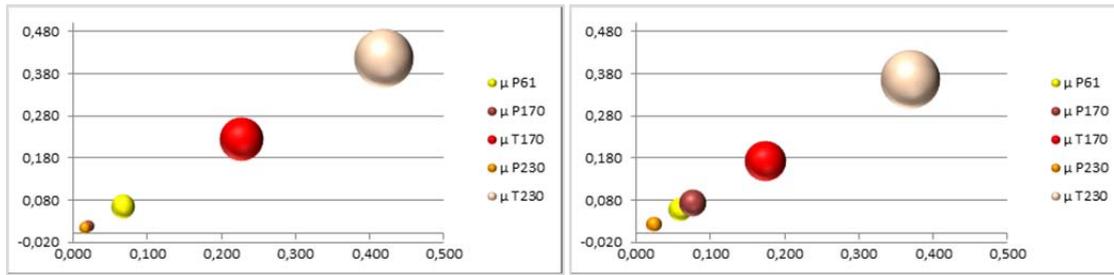


Figure 2-46: Static and kinetic friction - warp/weft

The warp/weft combination for the static friction show the best results for the twill fabrics T170 and T230, while the fabric P61 is very low and the fabrics P170 and P230 show no influence of the wool onto the panel. The kinetic friction show the same tendencies for the T170 and T230, but the P61 and P170 are low and the P230 show nearly no influence. The Figure 2-47 gives an overview over the combination weft/warp.



Figure 2-47: Static and kinetic friction - weft/warp

Here the mass per unit areas 230 g/m² fabrics P230 and T230 have the highest results, while P61 and T170 have low values and P170 show nearly no influence of the wool onto the panel. The kinetic friction coefficients show the same tendencies in the order of results but with more even space between them. Figure 2-48 presents the combination of weft/weft.



Figure 2-48: Static and kinetic friction - weft/weft

The weft/weft combination of T230 gives the highest difference between pure aramid and aramid/wool combinations for the static and the kinetic friction. Also the other twill fabric T170 shows a high influence of the wool onto the friction behaviour.

2.5.1.2 Conclusions

In total, the twill fabrics show the highest influence of the wool onto the frictional behaviour of aramid fabrics. The plain weave fabric results show nearly no influence of the wool onto the panels. The comparison of the weave direction shows the highest influence of the wool onto the warp/weft and the weft/weft combination.

-

2.5.2 Seam slippage

To determine the influence of the effect of seam slippage, four different woven aramid structures with different properties and pattern, are tested against shift by determining the seam slippage by using the fixed seam opening method. Due to this, the behaviour of stab resistance of the different aramid fabrics are tested according to the VPAM test instruction “Stab-and impact protection” (Test Standard VPAM KDIW 2004). The interdependence between the yarn slippage and the stab penetration is analysed. A better understanding of this process allows improving fabrics against stab attacks in future.

2.5.2.1 Materials

The four different high modulus aramid fabrics are tested, which represent a wide range of different parameters, like pattern, yarn density, thickness and fabric weight per square meter, which were presented before. To see the influences of mass per unit area and pattern, the plain and twill fabric with 170 g/m² P170 and T170 and the plain and twill fabrics with 230g/m², P230 and T230 are compared.

2.5.2.2 Methods

The fabrics are analysed through an optical observation as pictures are taken after the stab tests.

Stab resistance measurements of the aramid panels are tested for their resistance against stabbing according to the test instruction VPAM KDIW 2004 “Stich- und Schlagschutz” (Test Standard VPAM KDIW 2004). Panels consisting of 6 and 8 layers are presented. To find out differences between the taken test panels, the fall height is reduced to 28.5 cm, which equates to 6.9 Joule.

The seam slippage is measured with a tensile testing machine- Textechno Statimat ME, according to the common standard (ISO 13936-1). The sample is fixed into grab clamps with a clamping length of 100 mm and pulled with a constant speed of 50 mm/min. The stress-strain curves of samples without and with a defined seam are compared. The force is determined due to the distances of the curves, which are equivalent to the defined seam opening.

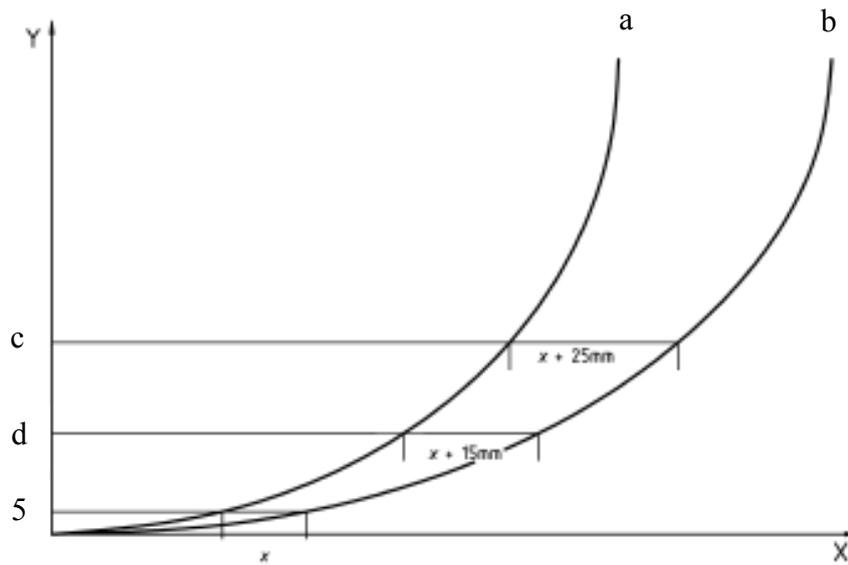


Figure 2-49: Automatic calculation of the seam slippage (ISO 13936-1)

Figure 2-49 shows the automatically done calculation of the seam slippage resistance for the example of 3 mm and 5 mm seam opening, where

- X= Elongation in mm
- Y = Force in Newton
- a = sample without seam
- b = sample with seam
- c = Force for a seam opening of 5 mm
- d = Force for a seam opening of 3 mm

The force, to open a defined seam can be calculated as

$$F_{seam\ opening\ x} = F_{x_{5N}} + (5 * L_{S_x}) \quad (18)$$

where x_{5N} is the distance between the two curves at a force of 5N, which acts as a perforce, to balance the extension of the fabric itself before testing.⁷

2.5.2.3 Results

2.5.2.3.1 Optical Observation

Figure 2-50 shows the optical observation of the penetration area of the fabrics after the stab test. The opening of the fabric can be seen for all fabrics, where the blade depresses the fabric and the primary filaments, which are in direct contact to the knife, migrate away from this

impact area. In this case, the filaments are not cut, just slide apart. It is assumed, that the low friction between the yarns lead to a high yarn slippage and the blade can ingress deeper.

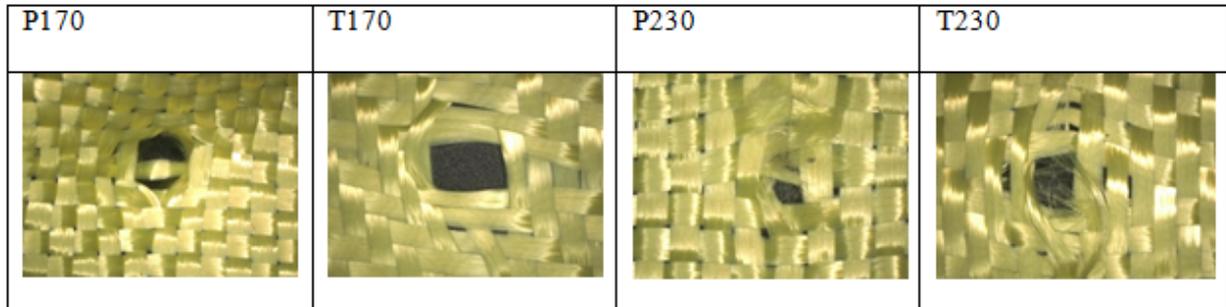


Figure 2-50: Optical observation of the fabric opening after the stab tests

2.5.2.3.2 Stab test results

Figure 2-51 shows the results of stab depth for panels out of six and eight layers of aramid. For both test series, the plain weave structures show better results than the twill weave structures. Due to the twill structures are looser than the plain weave fabrics, the yarns can slide apart easier and the knife can penetrate deeper.

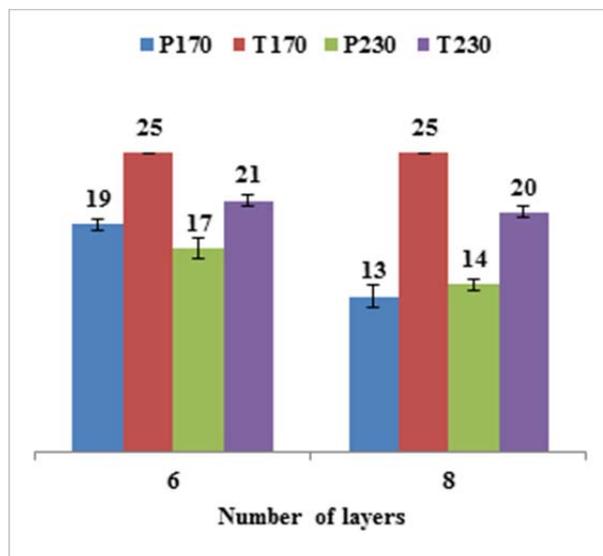


Figure 2-51: Stab depth of panels out of 6 and 8 layers

Comparing the results of the stab depth to the seam slippage results of these fabrics, the looser structures, which can be penetrated deeper, are also easier to slide apart during the determination of the seam slippage behaviour.

2.5.2.3.3 Seam slippage

The behaviour of slippage resistance of yarns at the seam was determined according to DIN EN ISO 13936-1.

For all four fabrics, tests were carried out in warp and weft direction. In table 2-9 an overview of the mean seam slippage results of the four different fabrics is presented.

Table 2-9: Results of seam slippage in warp and weft direction

Seam opening mm	P170 warp	P170 weft	P230 warp	P230 weft	T170 warp	T170 weft	T230 warp	T230 weft
mm	N							
6	10.39	9.79	25.97	25.86	5.57	5.32	3.11	4.11
8	15.74	15.09	37.22	35.15	7.10	6.54	5.72	6.45
10	19.83	20.64	47.49	42.78	8.40	8.40	8.03	9.34

Seam opening results at 6, 8 and 10 mm are presented in Figure 2-52, 2-53 and 2-54 respectively.

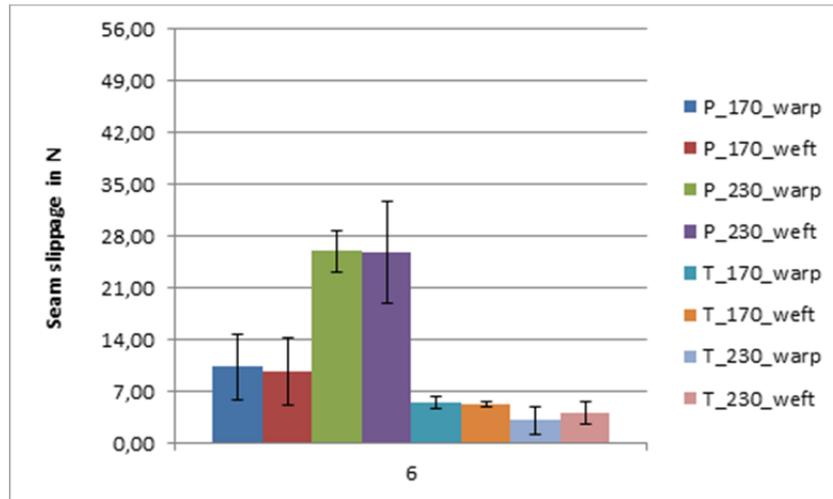


Figure 2-52: Seam slippage results for 6 mm seam opening

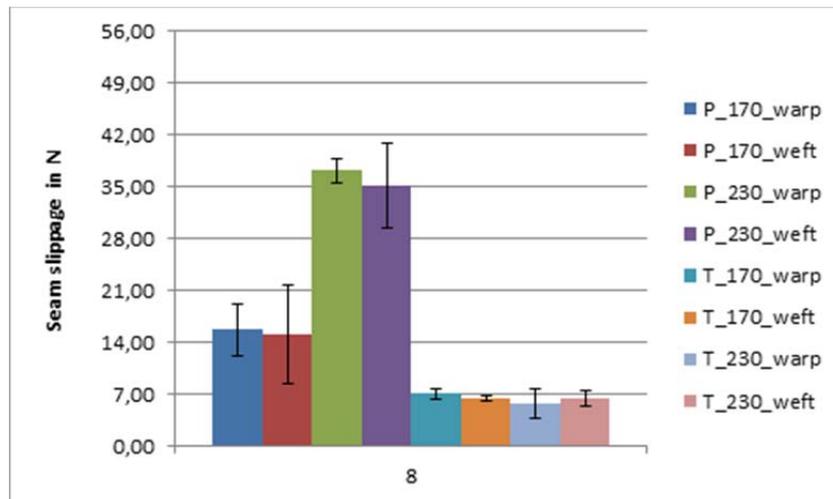


Figure 2-53: Seam slippage results for 8 mm seam opening

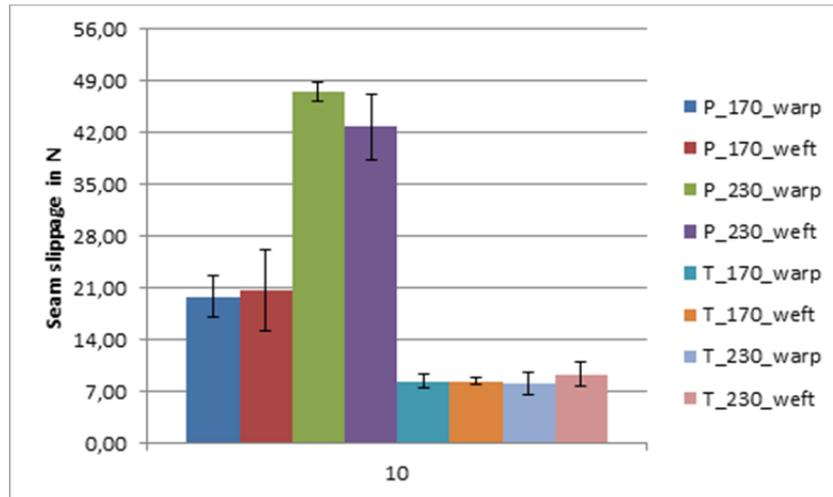


Figure 2-54: Seam slippage results for 10 mm seam opening

The results show, that there are no significant differences between the results of the both directions, like the deviations in Figures 2-52 to 2-54 show. Therefore an average of both results was analysed in the following tests after these series. Also the trend of results are visible, therefore an analysis of the interdependence between the stab depth results and the seam slippage results were just determined for the seam opening of 6 mm and 8 mm.

2.5.2.3.4 Influence of seam slippage resistance on the stab depth measurements

For the four different fabrics, the opening force was measured at a seam opening of 6, 8 and 10 mm. These results have been compared to the stab resistance of panels out of 6 and 8 layers. Interestingly the curves show an opposing trend, which confirms the assumption of interdependence between the seam slippage behaviour and the stab penetration depth results.

Figure 2-55 presents the stab depth values of the samples in comparison to a seam opening of 6 mm. The run of the curves goes in the opposite direction.

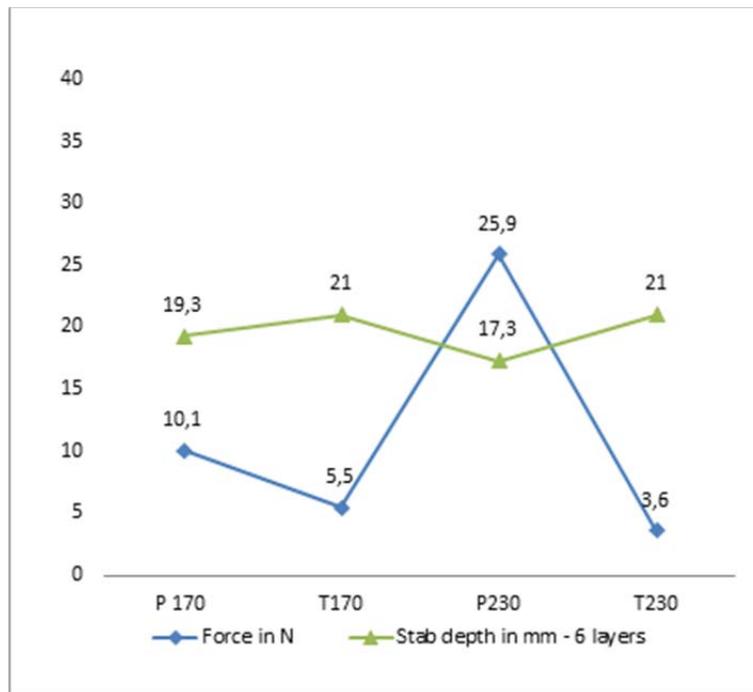


Figure 2-55: Comparison of seam opening at 6 mm with stab depth of 6 layers

When the force, to open the seam increases, the stab depth is lower. Also a decreasing of the force shows an increasing of the stab penetration. The influence of pattern and mass per unit area are also visible. The plain weave P230 show significant higher force values to open the seam with a result of 25.9 N, while the P170 just need 10.1N to open the seam for 6 mm. The twill weave fabrics are both really low in the force values with 5.5 and 3.6N. Comparing to the stab depth results of the twill fabrics, which show the same values, the interdependence is presented. A low seam slippage leads to a high stab depth. In Figure 2-56 the stab depth results are compared to a seam opening of 8 mm.

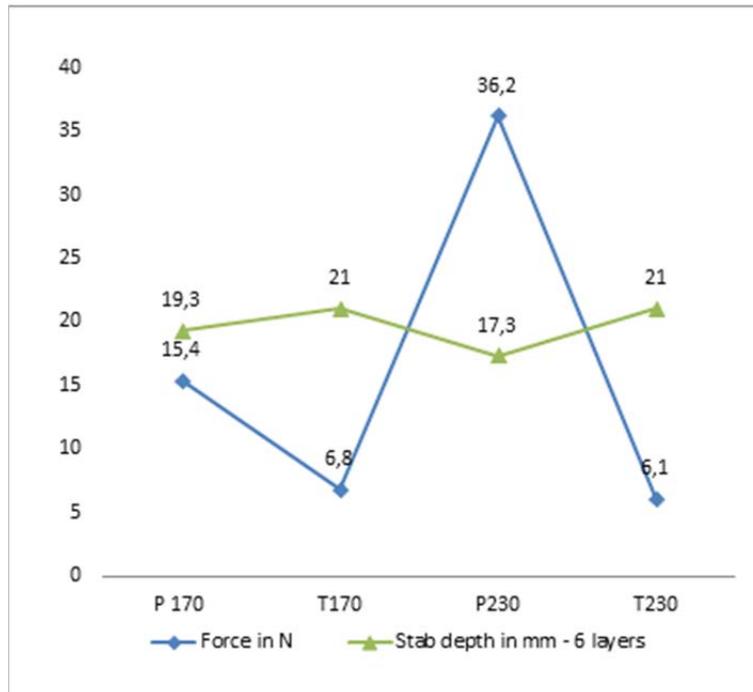


Figure 2-56: Comparison of seam opening at 8 mm with stab depth of 6 layers

While the force to open the seam from six to eight mm increases for the plain weave structures round about 5 to 10N, the force for the twill structures stay relatively stable. Like shown in Figure 2-56, they increase from 5.5 to 6.8 N for the P170 and from 3.6 to 6.1 N for the P230.

The stab depth penetration decreases from six to eight layers for both plain weave panels like Figure 2-57 demonstrates.

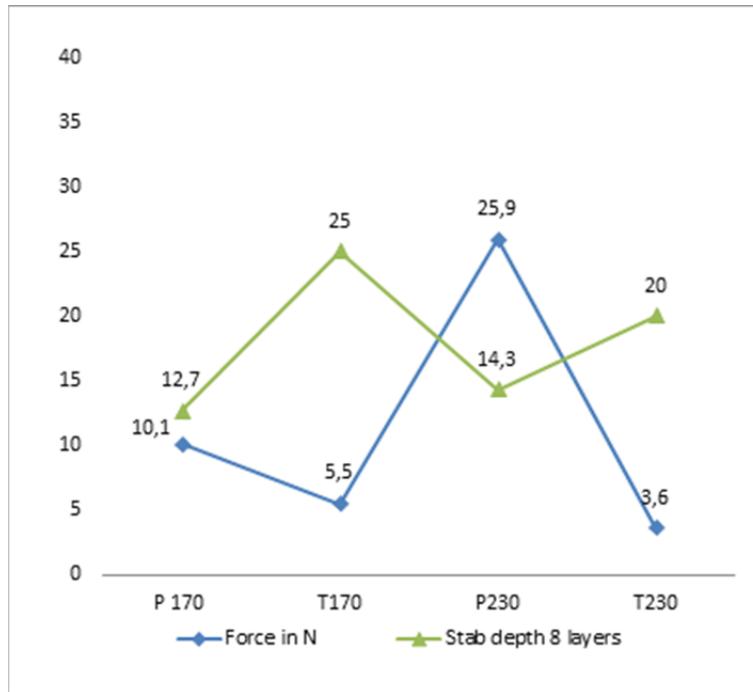


Figure 2-57: Comparison of seam opening at 6 mm with stab depth of 8 layers

The twill weaves panels increase or stays stable. Again, the results show a relationship between the stab test results and the seam slippage behaviour.

Figure 2-58 shows the results of a seam opening of eight mm and the stab depth results of eight layers of the panels.

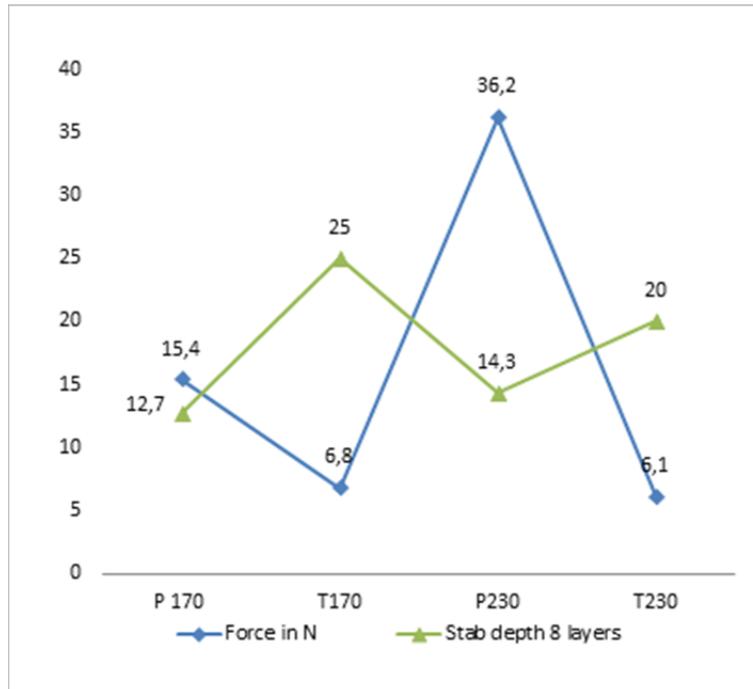


Figure 2-58: Comparison of seam opening at 8 mm with stab depth of 8 layers

A trend of the curves in opposite direction is also given here. All diagrams show, that the seam slippage results of the plain weave pattern show significant higher force results by increasing the mass per unit area, while the twill pattern fabrics have similar results.

2.5.2.4 Conclusions

Aramid yarns show a high migration of yarns in the fabric, which occurs openings in fabrics and lead to a decreasing of safety. Not only the stab penetration is important to analyse, also the seam slippage behaviour gives an impression of the stability of a fabric. The results show the relationship between the stab depth and the seam slippage. An increasing of the force to open a seam, presents also better results of the stab depth. Understanding the phenomenon of yarn sliding will help to forecast the fabric properties for safety garments but also for membranes or other applications.

2.5.3 Pullout

Due to the yarn slippage of aramid, the goal for the developer of stab resistance garments is to enhance the frictional behaviour of the fabric. The slippage of the yarns was already analysed by testing the seam slippage, where the force was measured to open a seam for a defined opening distance. Not just the opening of the fabric is of interest, but also the behaviour of the

yarns, when they are pulled-out. The most common methods how researchers the pull-out behaviour test, were already explained before. But in these methods, fabrics are clamped in at the sides, which lead to extensional stress in the fabric. Therefore a new method is developed, where these influences are prevented.

2.5.3.1 Materials

Two different fabrics are compared with each other to find out if there are influences on the pull-out behaviour for the different fabric constructions. The fabrics P230 and T230 with 230 grams per square meter each and seven threads per cm in both directions are chosen.

2.5.3.2 Methods

To prevent the extensional stress in the fabric area, a new test method is proposed, where the fabric is clamped on the top and the yarn, which will be pulled-out, is cut out. This yarn is clamped in the bottom clamp. Figure 2-59 presents an example for one pull-out test.

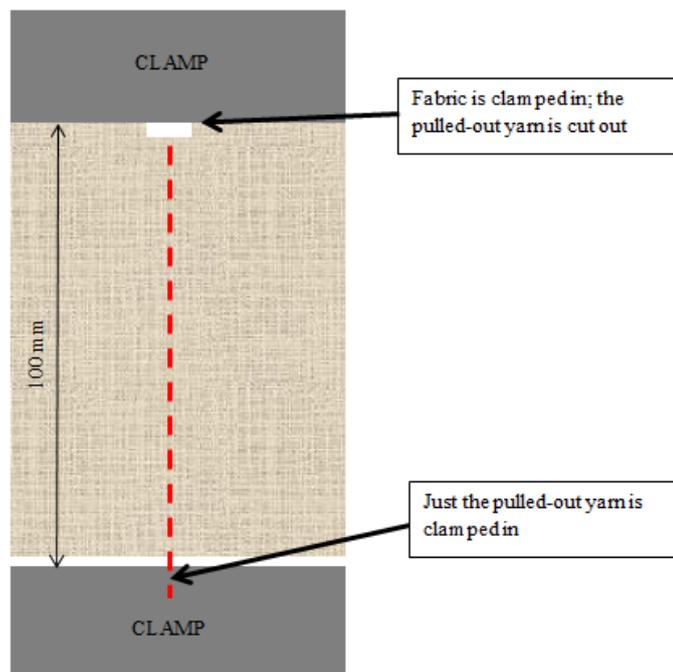


Figure 2-59: Schematic view of the measurement of the Pull-out forces

The test specimen are prepared with a width of 50 mm and the test speed is 100mm/min. Five tests are carried out per fabric direction and the mean values are compared.

In the beginning, the crimped yarn extends. After full extension, the first peak of the pull-out force is visible, where the kinetic region begins. The yarn is pulled through all crossing points

by the stick-slip effect. The stick moments are recorded, when the pulled-out yarn is passing over or under a filling yarn. They are divided in minimum and maximum values. Through the use of macros the maximum and minimum values were withdrawn from the data table with more than 6000 values. Figure 2-60 presents an individual value for fabric P230 to demonstrate the kind of analysis, which has been done.

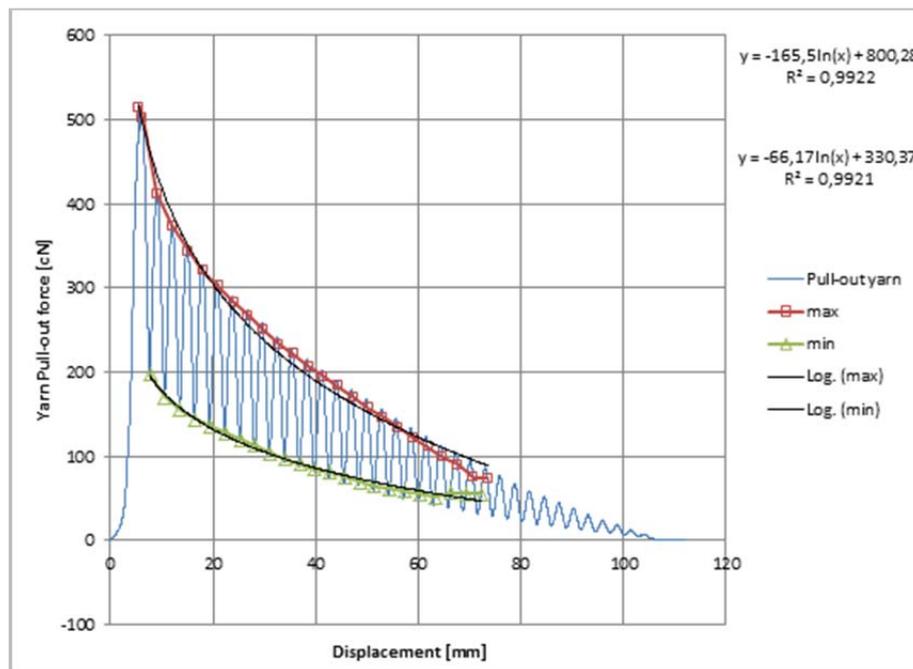


Figure 2-60: P230 Individual value of Pull-out test

The diagram shows a typical curve of a pull-out measurement with the maximum and minimum peaks, which present the stick motion of every yarn crossing point. The mean curves for the maximum and minimum curves are inserted and a logarithmic regression analysis is applied to find out statistical equation that described the function best. The logarithmic correlation coefficient $r = 0.992$ shows a very strong interrelationship between the decreasing pull-out forces and the displacement of the yarns. That means that the resistance of the pull-out yarn decreases by shortening the yarn length of the fabric. In the following, pull-out tests are carried out on the two fabrics P230 and T230.

Five individual tests have been done for each test series. Here the maximum and the minimum peaks were plotted in separate diagrams to demonstrate the comparability of the results.

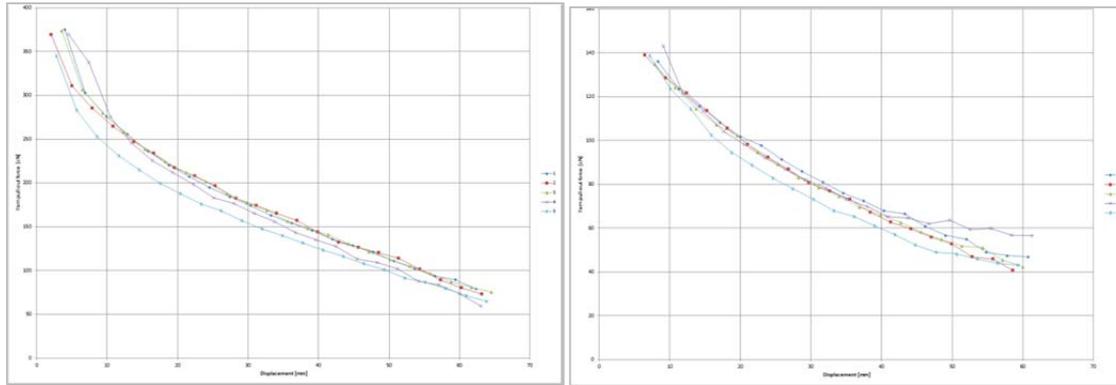


Figure 2-61: P230 warp - maximum and minimum peaks

Figure 2-61 presents the individual values of the pull-out forces of the P230 fabric in warp direction. The values are between 344.8cN and 375.1cN for the highest peak, which means the maximal resistance to pull out the thread in the first stick area. The mean value is 366.5cN. The minimum peak values for the P230 are between 134.9cN and 143.0cN.

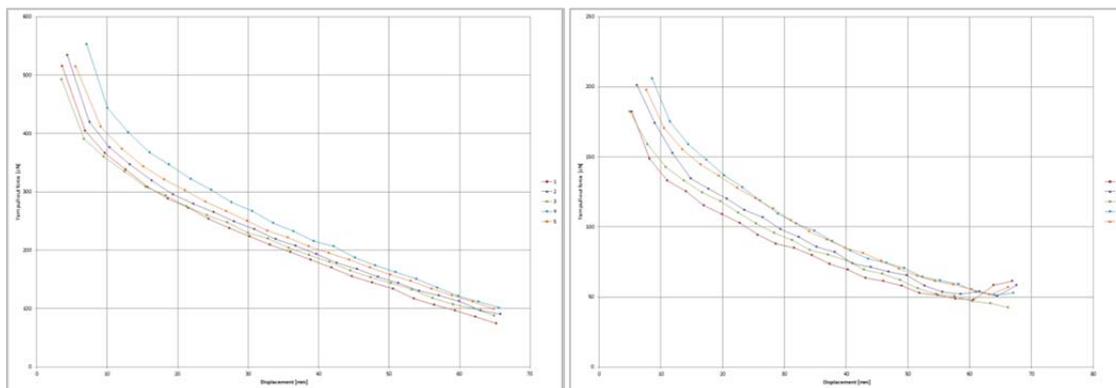


Figure 2-62: P230 weft - maximum and minimum peaks

Figure 2-62 presents the values for the plain weave fabric P230 in weft direction. The maximum values are between 492.2cN and 553.0cN. The minimum values present results between 182.2cN and 206.0cN.

The mean values for the maximum peaks and minimum peaks for warp and weft have been compared, which is presented in the following charts.

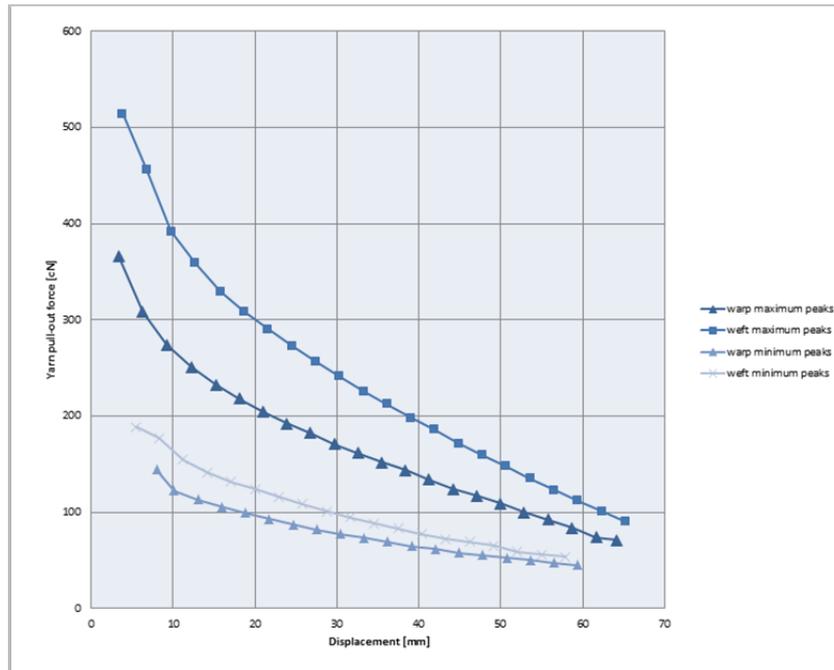


Figure 2-63: P230 Comparison of warp and weft

The pull-out forces of the weft yarns are higher than the values for pulling-out the warp yarns. The maximum and the minimum peaks present the same behaviour, like Figure 2-63 shows. In the following charts, the individual values for the maximum and minimum peaks of the twill fabric T230 with the same mass per unit area like the plain fabric P230, which was analysed before, are presented; separated in warp and weft direction.

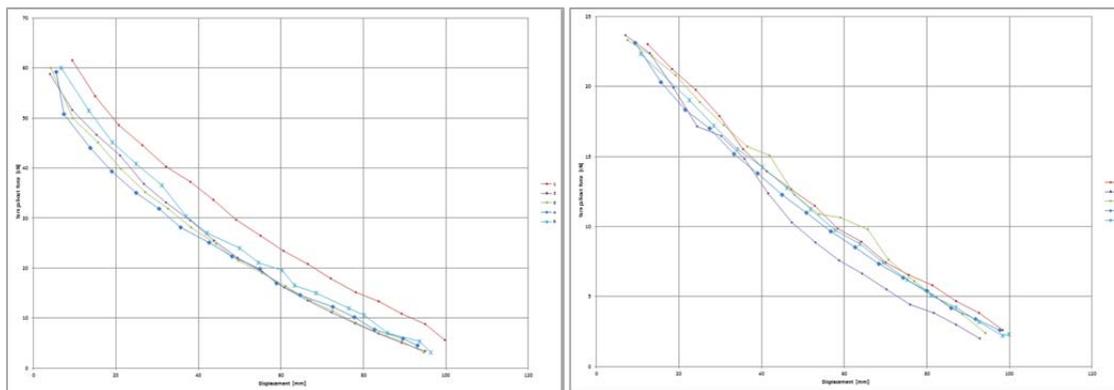


Figure 2-64: T230 warp - maximum and minimum peaks

The maximum results for the twill fabric T230 are between 58.7cN and 61.5cN and the minimum results show values between 22.3cN and 23.6cN.

The results in weft direction are as presented in Figure 2-65:

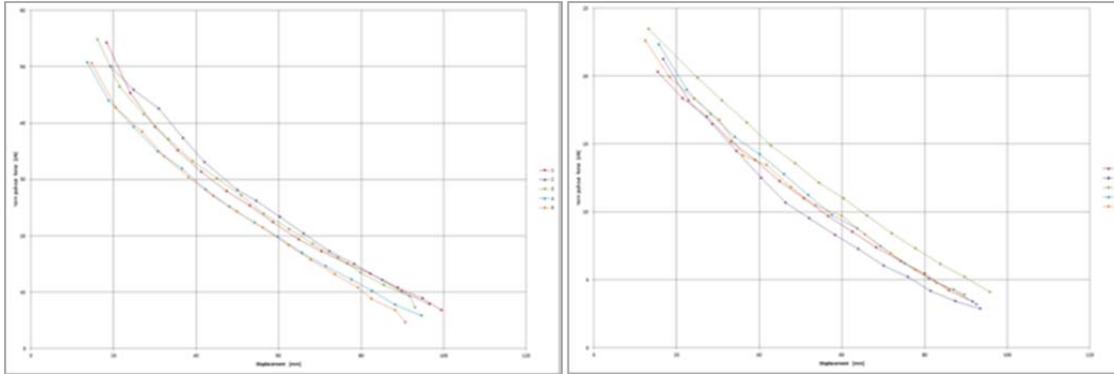


Figure 2-65: T230 weft - maximum and minimum peaks

The maximum peaks of the pull-out test in weft direction show values between 50.1cN and 54.8cN. To pull out a yarn, forces between 20.3cN and 23.5cN are required. The comparison of the results in warp and weft direction is presented in the following Figure (Figure 2-66).

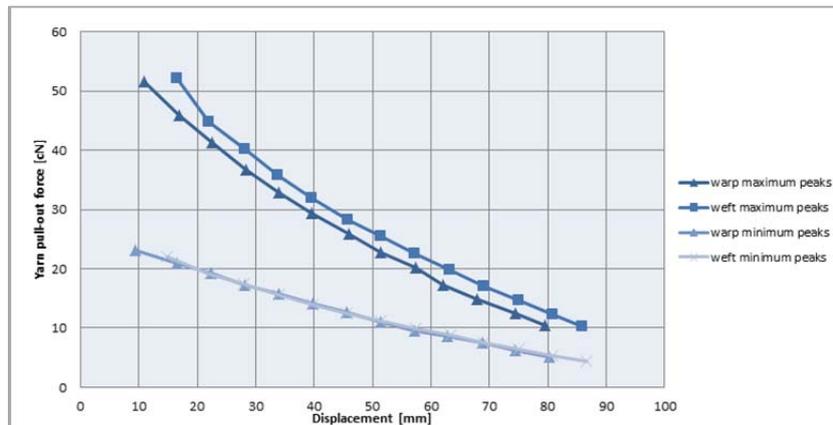


Figure 2-66: T230 Comparison of warp and weft

The pull-out forces in warp and weft direction of the twill pattern are comparable. They show the same behaviour in the force, which is required to pull out one thread; just the displacement moment varies. Next to that, the plain and twill patterns are compared, to find out differences in the behaviour of the different structures. Figure 2-67 presents the maximum values and Figure 2-68 the minimum values.

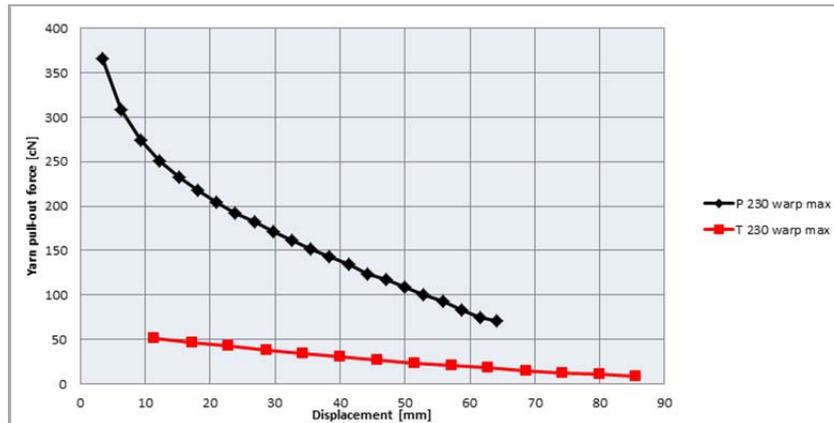


Figure 2-67: Comparison of plain and twill – warp max. values

The maximum force to pull out a twill yarn in warp direction is just 50cN, like it can be seen in Figure 2-67, while the warp threads of the plain weave pattern give values of more than 350cN, which is seven times higher than for the twill fabric.

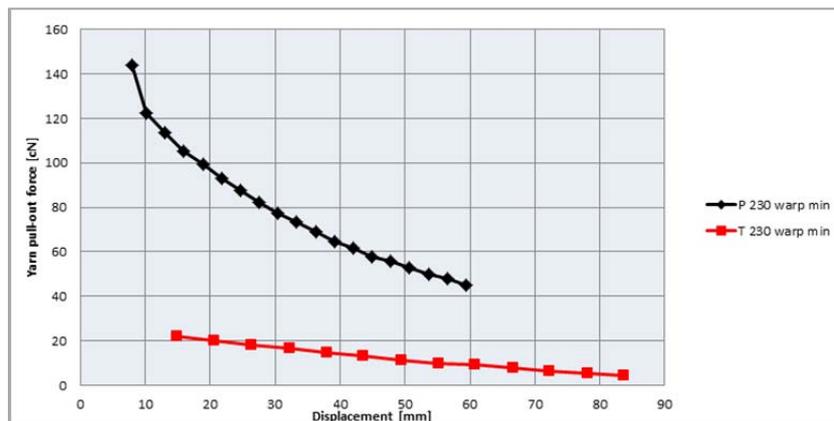


Figure 2-68: Comparison of plain and twill – warp min. values

The minimum peaks, which are presented in Figure 2-68, show the same behaviour as the maximum peaks. To pull out a yarn of the twill fabric, a maximum force of 20cN is required while the P230 starts at a value above 140cN.

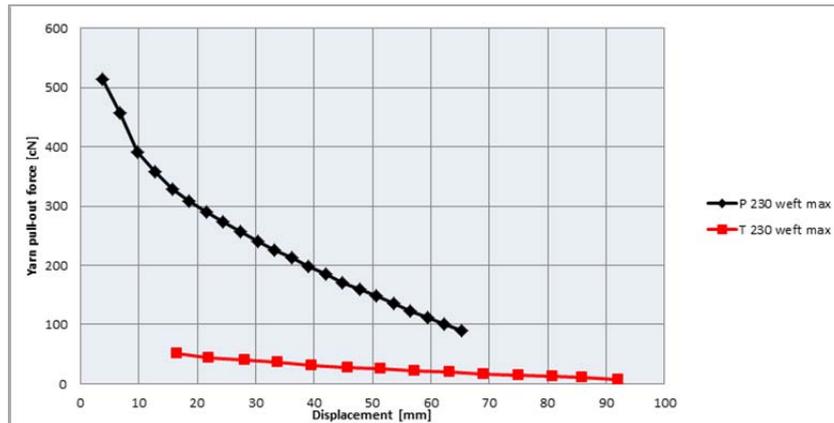


Figure 2-69: Comparison of plain and twill – weft max. values

Also the weft direction presents a similar behaviour of the threads. Here the difference between the patterns is even higher than in warp direction. To complete the test series, also the minimum peaks in weft direction of the two different patterns are compared, like Figure 2-69 presents.

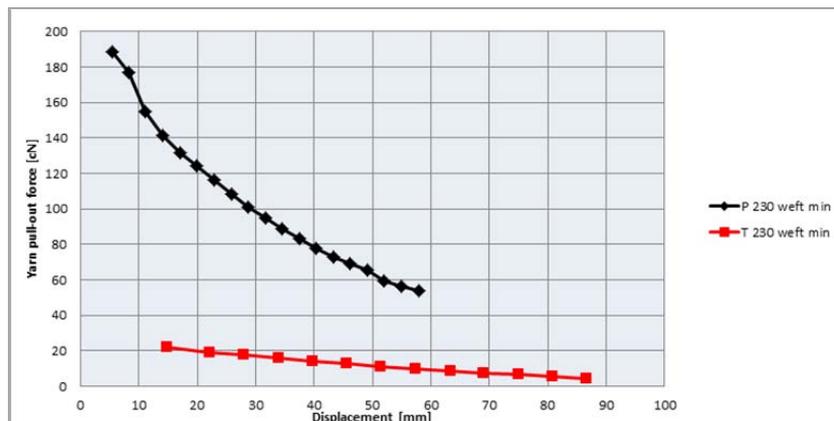


Figure 2-70: Comparison of plain and twill – weft min. values

The pull-out forces of the minimum peaks show the same behaviour as the maximum peaks. To pull out a yarn of the twill fabric T230, a maximum force of 20cN is required while the P230 starts at a value above 190cN.

2.5.3.3 Conclusion

Based on the tests carried out it can initially be hypothesized that the constructional characteristics and the resulting fabric properties of aramids exercise a significant influence on the effect of the stab resistance behaviour. The results show that yarn pull-out force depends on the pattern and for plain weave fabrics also on the yarn direction in the fabric is important. In general, the pull-out force of P230 was higher than that of T230. That shows that the pull-out forces of tight plain fabrics are higher than those of loose fabrics like twill fabrics. Also the weft directional yarn pull-out forces of twill fabrics were slightly higher than those of warp directional yarn pull-out forces. Plain weave fabrics show this effect much stronger; the weft directional pull-out force is much higher than the warp directional force. Maximum peak curves give a similar behaviour like minimum peak curves. The results confirm the behaviour of the different fabric types on penetration. The twill fabric allows a thread to be displaced clearly easier than a plain one. This is reflected both in the pull-out forces where the twill gives significantly lower results, and in the penetration, where the easier thread displacement permits a deeper penetration.

CHAPTER 3

3 Improvement of the stab resistance

An important point in the context of stab protection applications is to stabilize the fabric to prevent the displacement of the threads so that the knife is required to cut the fabric instead of separation (Horsfall 2012). As already mentioned in previous chapters, the slippage of the aramid yarns during the penetration process is a main problem for stab protection because of their smoothness. The displacing of the individual yarns does not need much energy, which is why a penetration with a knife increases. Since the research objective of this work is to make a contribution to the development and optimization of stab-resistant structures of pure textile solutions, considerations were made to combine other textile materials with the aramid fabric to stabilize the fabric structures. The goal is to increase the surface friction to prevent the sliding of the yarns. The influence of wool on the surface's friction behaviour was explained before. It is assumed, that the wool's surface interacts with the smooth surface of the aramid layer during the penetration process. Therefore a wool fabric with a rough and hairy surface was used, to give a higher support to the aramid fabrics and to hold them together. Accordingly tests were carried out by inserting a wool layer on the surface of aramid panels and to increase the protection level.

3.1 Insertion of wool

The tests showed that placing a layer of wool fabric on the top of the aramid panel changes the penetration behaviour.

3.1.1 Materials

For this investigation, the stab resistance of the five aramid fabrics with different properties and patterns combined with one layer of wool on top and at the bottom of the panel has been tested and compared against pure aramid panels. All plain weave fabrics, which are P61, P170 and P230 and the two twill fabrics T170 and T230 are tested and compared to panels with the twill wool fabric.

3.1.2 Methods

Stab resistance measurements of the aramid fabrics are performed, which represent a wide range of different parameters, like pattern, yarn density, thickness and fabric weight per square meter. To show the frictional interaction between the fabric layers out of wool and

aramid, they are tested for their resistance against stabbing according to the test instruction like mentioned in the chapters before (Test Standard VPAM KDIW 2004).

3.1.2.1 Optical observation

The tests are performed in two steps. First of all, pictures are taken with a high-speed camera, to see the penetration in this moment, when the blade cuts-into the fabric. Here the general differences between panels with and without wool are given, to show the mechanism of the influence of the wool layer in these panels. Additionally the stab opening in the fabrics is measured for all fabric panels. Also the stab recess in the aramid layers is evaluated optically, using a digital microscope.

3.1.2.2 Stab depth measurement

Test panels out of six to ten layers are tested. To find out differences between the fabrics, the fall height is reduced to a height of 28.5 cm, which equates to 6.9 Joule. Afterwards the same panels with a layer of wool on the top and bottom are tested. A wool twill fabric is chosen, which is often used in industry. Future tests will show the influence of wool fabrics with different weights and patterns.

3.1.3 Results

The experimental results confirm that wool can increase the stab resistance of body armour panels; however the results depend on the properties and pattern of the aramid fabrics.



Figure 3-1: Stab behaviour of an aramid fabric

Figure 3-1 shows a typical behaviour of an aramid fabric layer during the penetration process.

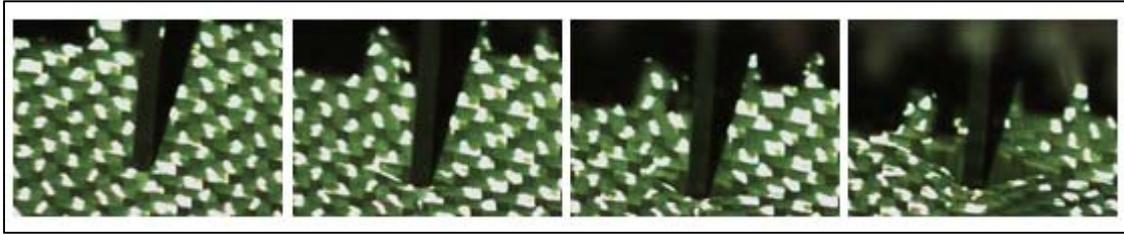


Figure 3-2: Picture sequence of the stab penetration of an aramid fabric

The picture sequence (Figure 3-2) shows the moment when the blade penetrates the woven fabric: the blade depresses the fabric and the primary filaments, which are in direct contact to the knife, migrate away from this impact area. In this case, the filaments are not cut, but sliding apart. It is assumed, that the low friction between the yarns lead to a high yarn slippage and the blade can ingress deeper. Therefore an additional test series was made with a layer of wool on the top and bottom side. The pictures of this test run are presented in Figure 3-3.

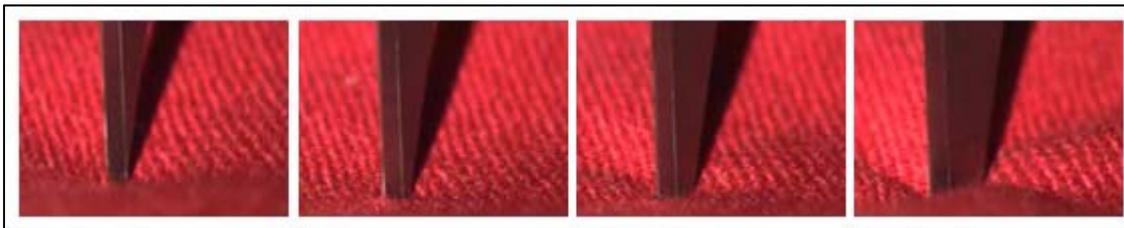


Figure 3-3: Picture sequence of the stab penetration of a wool fabric

The blade depresses the wool layer and penetrates it through a cut. The woven wool fabric may absorb the kinetic energy by deflection of the fabric, a friction at the contact region, fabric shearing and crimp behaviour. Sadegh and Cavallaro (Sadegh, Cavallaro 2012) described these steps as a normal impact between a projectile and a plain woven fabric, but it is applicable as well for a blade penetration, but the importance and the starting point of the different phenomena over the behaviour will be different. The following figures show the effect of the wool layers on the first aramid layer after the penetration. But not just the first layer shows these effects. All layers show these different effects between panels with and without wool layers. All pictures were taken under a digital microscope with a 20x magnification.

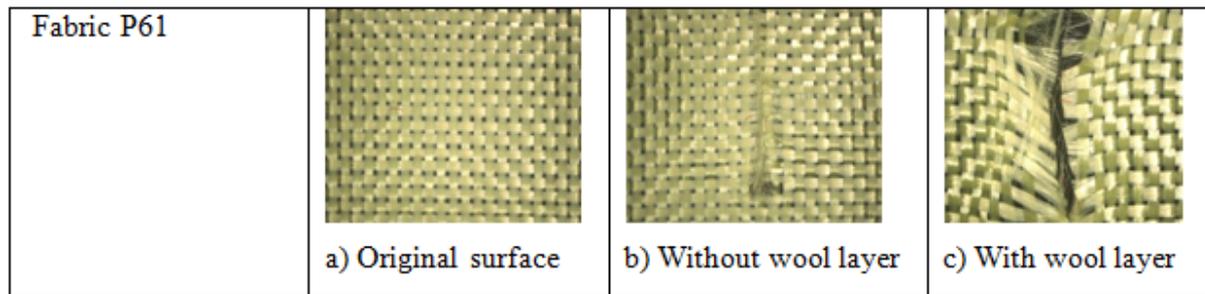


Figure 3-4: Optical observation of stabbing for fabric P61

Fabric P61 is a thin plain weave fabric with a haptic impression. The fabric is relatively tough with hardly any slippage. Because of that, it is assumed, that no migration occurs during the stab test of the aramid panel. Therefore the inserted wool layer influences the depth of the stab penetration of the panel not that distinctive (Figure 3-4).

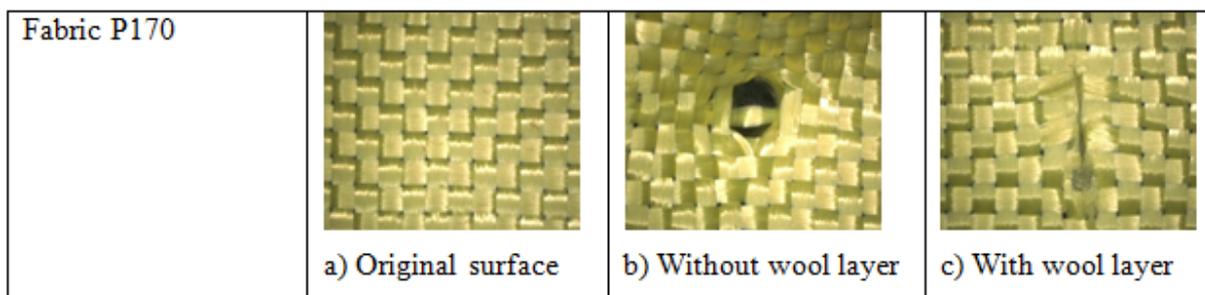


Figure 3-5: Optical observation of stabbing for fabric P170

Fabric P170 shows a yarn migration away from the impact area, when no wool layer is used, while the wool layer enables the blade to cut the filaments. In Figure 3-5 the optical results are presented. It is assumed, that the high friction of wool avoids the smooth filaments to migrate, which would create openings in the structure. The cut into the wool layer absorbs more kinetic energy, which leads to a lower energy level to penetrate the fabric.

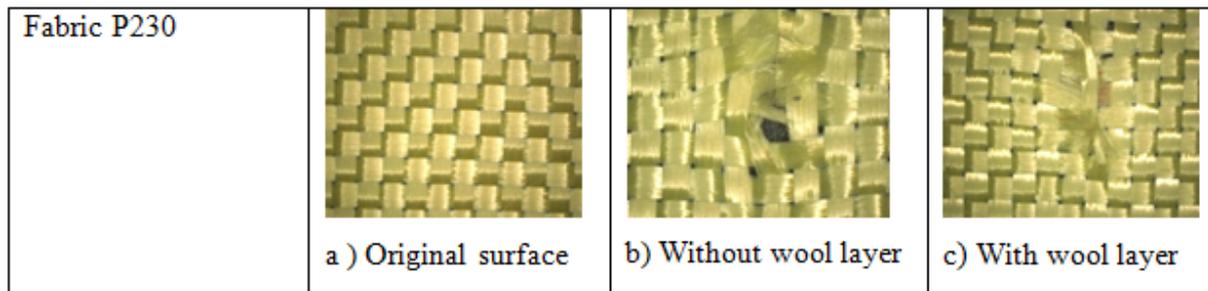


Figure 3-6: Optical observation of stabbing for fabric P230

Also the plain woven fabric P230, presented in Figure 3-6, shows a similar effect of inserting wool in the panel. While the panel without wool shows effects of migration, but also pull-out of yarns, in the wool-including panel avoids the migration of the filaments and absorbs more energy to cut the layers.

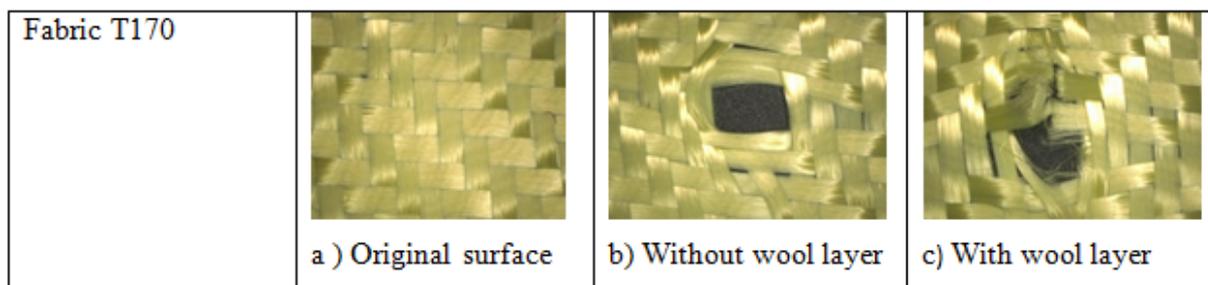


Figure 3-7: Optical observation of stabbing for fabric T170

The engaged twill fabrics show a loose woven structure, which leads to a high slippage of yarns. Figure 3-7 shows the effect of knife penetration, when the filaments are migrating in the panel without wool. There can be seen a small migration in the wool including panel, but in this case most of the yarns are cut in this area.

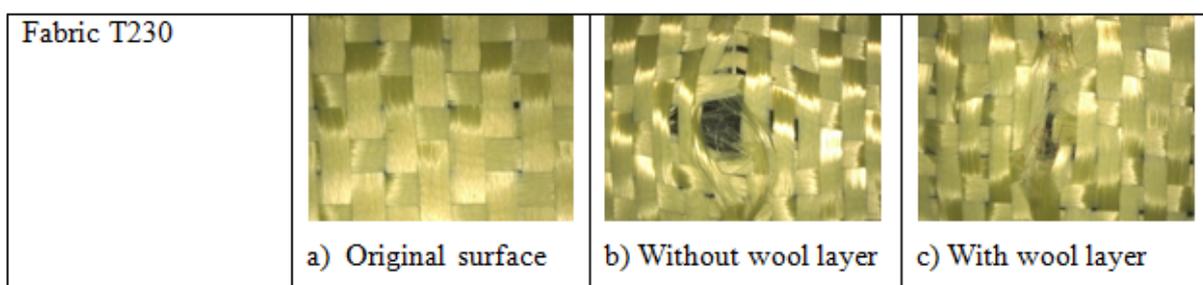


Figure 3-8: Optical observation of stabbing for fabric T230

Also the twill woven fabric T230 shows effects of a high migration of the filaments in the pure aramid panel, like shown in Figure 3-8. Both twill fabrics show a high yarn slippage in a

subjective tactile sensation. That means that the yarn sliding apart does not need much energy. For the knife, it is easy to separate the yarns to penetrate the panel. Therefore it is assumed that more energy is required, to cut the layers, than penetrate the layers. That corroborates the belief, that due to this, the injuries are less dangerous because of a lower penetration depth.

3.1.3.1 Stab depth results

In the second part of the analysis, the stab penetration is measured and the results are given and compared between panels with and without a wool layer. The values of stab depth for different panels of 6, 7 and up to 10 layers are depicted. The wool layer is always additional to the aramid layers, which leads to a panel out of 6 plus 2 wool layers and up to 10 aramid plus 2 wool layers, consequential 8, 9 and up to 12 layers. In all graphs the measurement results of the stab depth in mm are inserted and the significant differences are shown additionally. The lower the values are, the better the results and more harmless the injuries for the human.

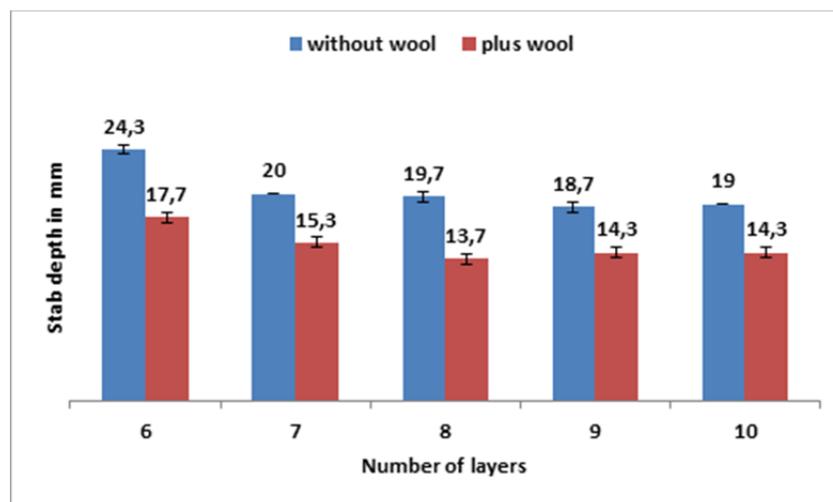


Figure 3-9: Stab depth results for fabric P61

Figure 3-9 gives the results of stab depth measurements of fabric P61, without and with wool. Comparing the two bar charts, the wool layer increases the results between 4-7 mm. With numbers between 7-10 layers, the results are relatively constant for both test series.

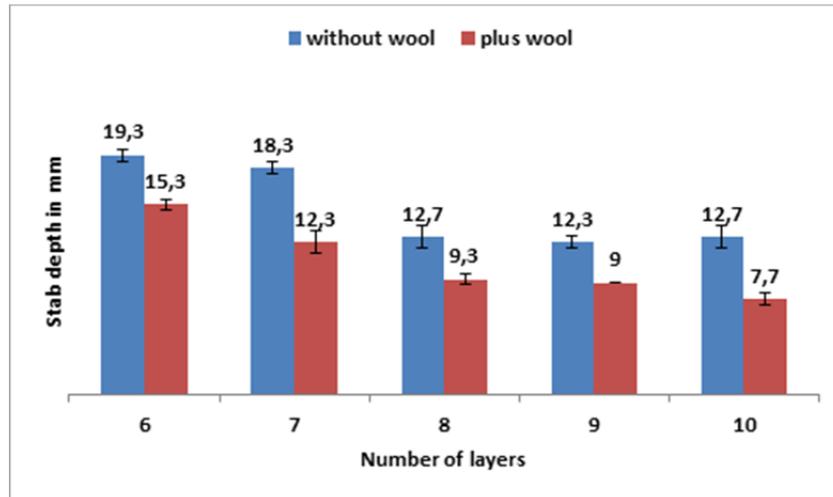


Figure 3-10: Stab depth results for fabric P170

An analysis of Figure 3-10 shows the curves of the two test panels of the plain weave fabric P170. A yarn with a fineness of 127 tex and 7 threads per cm is inserted. The adjustments are similar in warp and weft direction. The curve without wool shows a leap from seven to eight layers, where the stab depth decreases about 6 mm and stays stable with up to ten layers. The results of the panel with wool differ to this curve. Every additional layer shows better results. An increase in stab penetrations between 3-6 mm is given by inserting the wool layer into the panel.

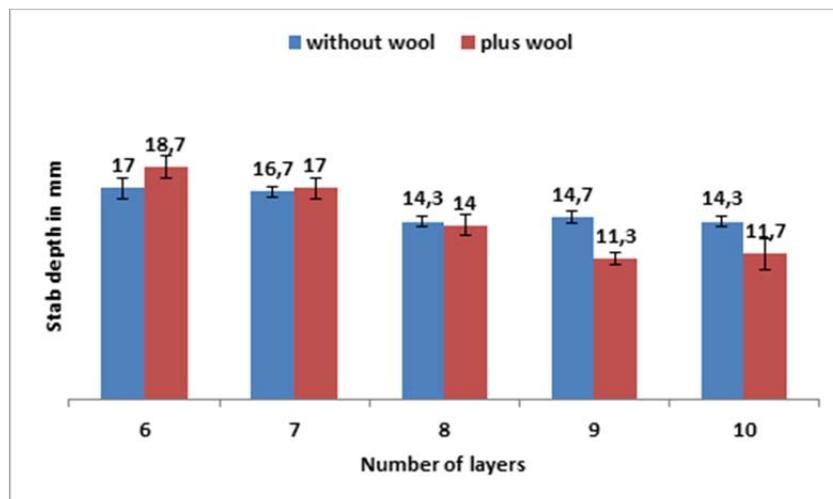


Figure 3-11: Stab depth results for fabric P230

The third plain weave fabric P230 is presented in Figure 3-11. A yarn of 158 tex with a fabric density of 7 threads per cm is used for this fabric. Between six and eight layers, the wool layer shows no effect on the stab depth results of the panel. A comparison between both test series

shows similar results. The wool starts to influence the stab depth at nine layers and above. A lower amount of layers show similar results. In comparison to the plain weave fabric P170, which is designed with the same parameters except for the yarn count, the fabric with the lower yarn count of 127 tex shows better results in stab resistance than the fabric P230 with 158 tex.

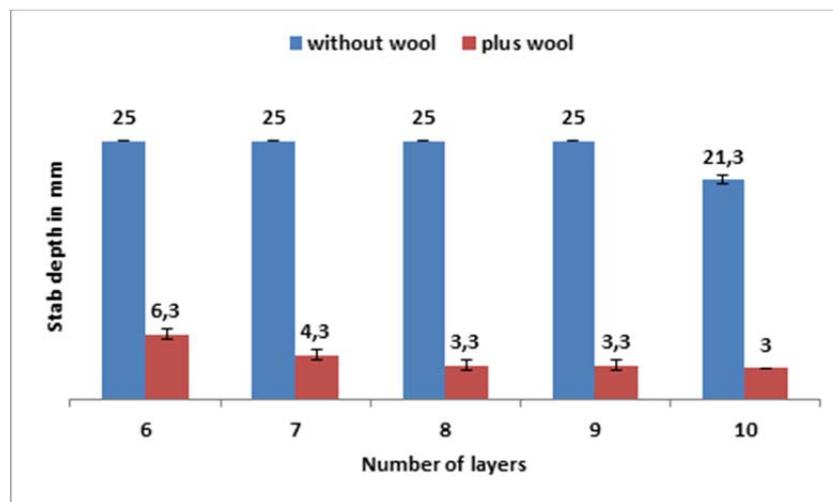


Figure 3-12: Stab depth results for fabric T170

The twill fabric T170, presented in Figure 3-12, shows a significant effect of holding the yarn in place, caused by inserting the wool layer. All results without wool show stab depths, which lead to fatal injuries. Inserting wool into this panel leads to excellent results also in a lower area of layers. The twill fabric T170 and the plain weave fabric P170 are produced with the same parameters, like yarn count and fabric density, but with a different pattern. The plain weave panel without wool show significant better results than the twill fabric. By inserting wool into the panels, the twill is influenced more by the wool and this leads to excellent results, which are better than the results of the plain weave pattern.

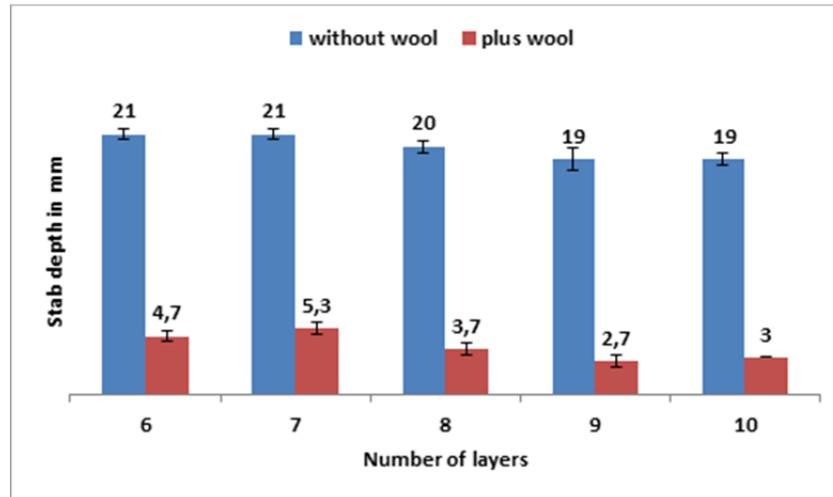


Figure 3-13: Stab depth results for fabric T230

The second twill fabric T230 is presented in Figure 3-13. This panel without wool shows good values for stab penetration in general, but the increasing number of layers gives no better results. The stab depth results between six and ten layers are nearly the same. It is assumed, that the knife always separates the yarns apart, so the number of layers have no significant influence on the stab depth of the panel. Also the panel with wool show very similar results between the number of layers, but in total, the wool layer leads to better values of about 10 mm. In comparison to the plain weave fabric P230 which contains the same parameters except the pattern, the results of the panel without wool show nearly the same stab depth results, but the influence of the wool is presented clearly in the twill fabric panel. Comparing the two twill fabrics with just different yarn density values, both test series show excellent results in the panel with wool layers. It is assumed, that especially the twill fabrics, which have a looser structure can be improved by inserting wool into the panel. Differences of up to 10 mm and more between the panels are shown. Wool affects a cutting instead of sliding apart, which leads to a higher energy absorption. The knife can't penetrate the panel as deep as without wool. Plain structures show better results in general, but can also be improved by a wool layer. To show, that the exchange of two aramid layers by wool layers still increases the stab resistance of the most aramid woven fabrics, the impact forces of the panels were determined, where panels with the same number of layers were compared. That means that 8 layers of an aramid panel were compared to a panel, where two layers were replaced by two wool layers. Table 3-1 gives the average results in of the mean impact force in Newton for these panels.

Table 3-1: The mean impact force values for aramid panels with and without wool

	8 layers	8 layers including wool	9 layers	9 layers including wool	10 layers	10 layers including wool
	N	N	N	N	N	N
P61	34.9	38.8	36.7	44.9	36.1	50.1
P170	54.1	44.9	55.8	55.8	54.1	69.4
P230	48	36.7	46.7	40.4	48	49.1
T170	27.5	109	27.5	159.7	32.2	208.1
T230	55.8	146.1	46.7	129.6	48	185.6

The impact forces are also presented in form of a diagram in the following Figure.

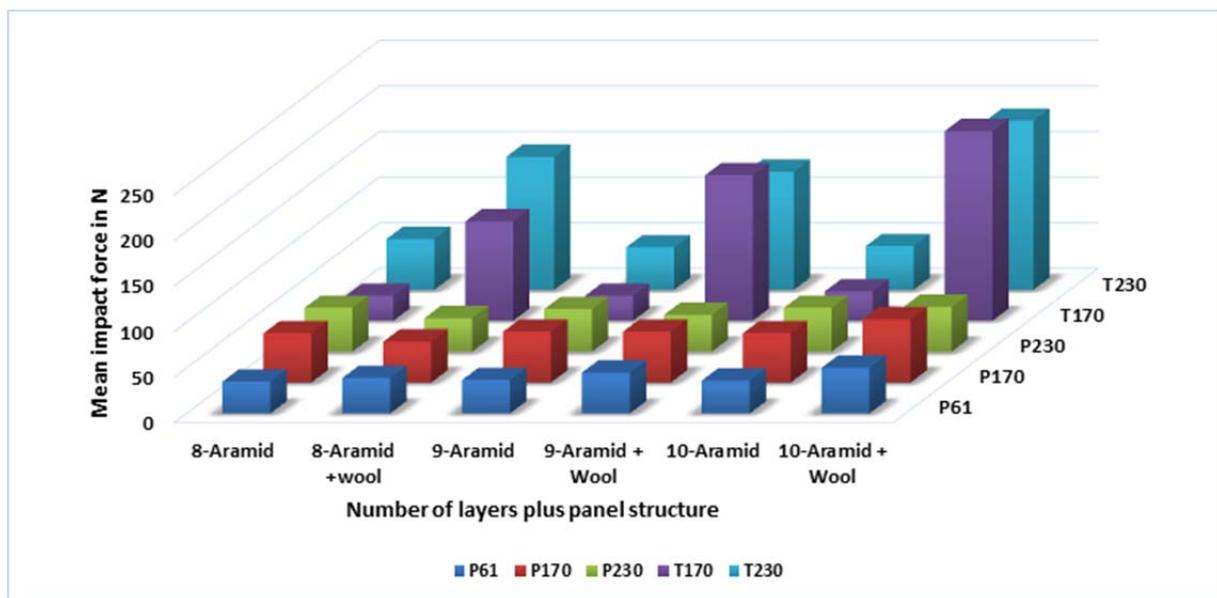


Figure 3-14: Impact forces of aramid panels with and without wool

The diagram in Figure 3-14 shows the comparison of the average impact force of selected structures. It is again very clear, that the pure aramid structures can be penetrated using significantly lower average impact forces, compared to the same structures combined with a wool layer.

3.1.3.2 Conclusions

Various aramid structures have been compared to panels with an outer layer of wool on top and at the bottom. The influence of wool has been investigated first by an optical observation

of the fabric surface. It is shown, that wool prevents the yarn sliding of the below aramid layer.

Two other assumptions can be derived, analysing the combined structure with the wool fabric. It seems that the insertion of wool is able to contribute to a stabilization of the aramid fabric, where it reduces the sliding apart of the filaments during the stab penetration and causes a cut, which absorbs more energy. Furthermore, it can be assumed that an improvement in the penetration depth of the blade through the use of wool is achievable mostly at those fabrics where the threads move very easily and can be displaced, like it can be seen in the twill structures. This improvement is noticeable only when the wool fabric is used as an outer protective layer on the aramid layers.

Measuring the stab depth, the twill fabrics show the highest influence of inserting wool into the panels. The investigation demonstrates that inserting wool into a protection panel can lead to achieving acceptable stab depth values with fewer layers. This leads to a weight reduction and improved wear comfort of the soft panels.

3.2 Development of blend yarns with wool

The previous chapter showed the positive influence onto the stab resistance laying a layer of wool onto the stab resistant panel. To increase the friction coefficient of the fabric itself, wool will be inserted into the panel. A reason for this consideration is the fact, that the fabric friction is influenced by the yarn friction, like already mentioned before. Also the yarn friction is influenced by yarn structural and bulk parameters.

3.2.1 Materials

To find the best combination of aramid and wool blend hollow spindle yarns with the highest friction coefficient, three yarns with different twists per meter between 50 and 200 planned twists per meter were produced on a Saurer hollow spindle spinning machine ESP-SM-10, like presented in Figure 3-15. The core yarn consists out of an aramid yarn with a fineness of 930 dtex and the cover yarn is a wool staple yarn with a fineness of 28.8 tex.

Following parameters are used:

Table 3-2: Machine parameter for blending yarns

Twists/m	Spindle speed (ns/min)	Delivery speed (m/min)	Yarn count (dtex)
52	2600	50	1160
103	4320	42.1	1200
202	4910	24.3	1190

The produced twists per meter vary to the planned twists per meter. The reason is that the twists per meter are decided by the machine delivery speed and spindle speed. So an exact adjustment of the twists is not possible.



Figure 3-15: Saurer hollow spindle spinning machine ESP-SM-10

3.2.2 Methods

One method is to blend the aramid yarn with a wool yarn into a core yarn. This is done with a hollow spindle spinning machine, where the yarn is composed of core yarn and cover yarn. In a hollow spindle spinning process, a yarn package which is fixed to the spindle, rotates at a high speed around the core yarn to form the hollow spindle spinning yarn which has a unique

yarn structure. In this case, aramid filament yarn is used as core yarn, because it provides excellent tensile and stab resistant properties and a wool yarn as the cover yarn, because of its high friction, caused by the scales on its surface. Combinations of both provide the favourable properties of both yarns and modify the structures and properties of both yarns.

3.2.3 Results

3.2.3.1 Friction coefficient measurement

To measure the friction of a yarn, the calculation is done after Euler, who found the relationship between the forces in a system, where a yarn running over a curved surface and the frictional force is determined by the angle of contact with the surface and the tension before and after the side of the contact. The tension on the uptake side is always higher than on the feed side as the motion of the yarn is resisted by the frictional force:

$$\frac{T_1}{T_2} = e^{\mu\theta} \quad (19)$$

and

$$\mu = \left(\frac{1}{\theta}\right) \ln\left(\frac{T_1}{T_2}\right) \quad (20)$$

where θ is the angular contact in radians, μ is the coefficient of friction, T_1 the output tension and T_2 the input tension. A general way to measure yarn friction is to run it round a solid rod and measure the friction by using the above relationship. The principle is presented in Figure 3-16.

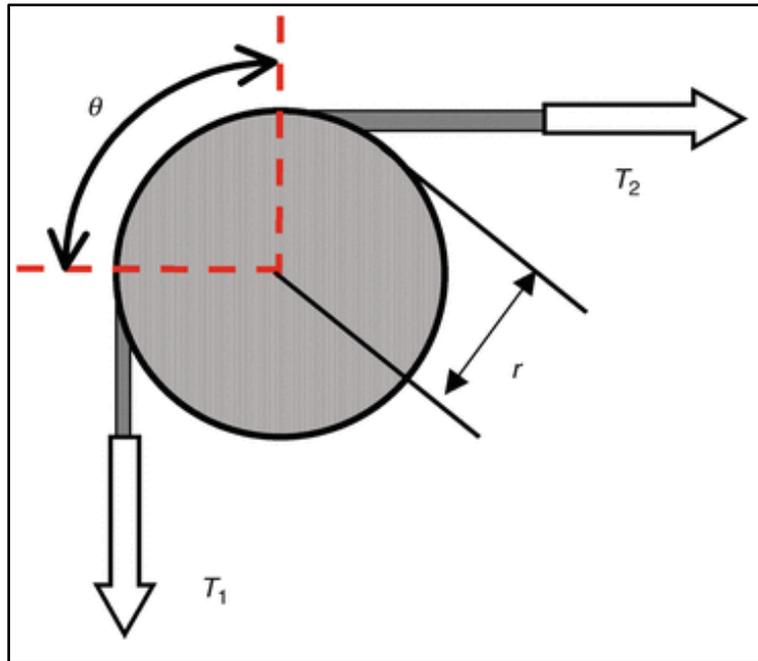


Figure 3-16: Principle of friction measurement (Wang, Chung 2013)

The yarn friction coefficient has been tested according yarn to solid material friction method, (ASTM D3108-01) where a yarn runs over the wheel surface of the KFF-C –universal spooling machine made by Jakob Müller. The frictional force of the yarns was identified by two sensors, where the relationship between force and the output voltage of the sensors was calculated. The principle of measurement is presented in Figure 3-17.

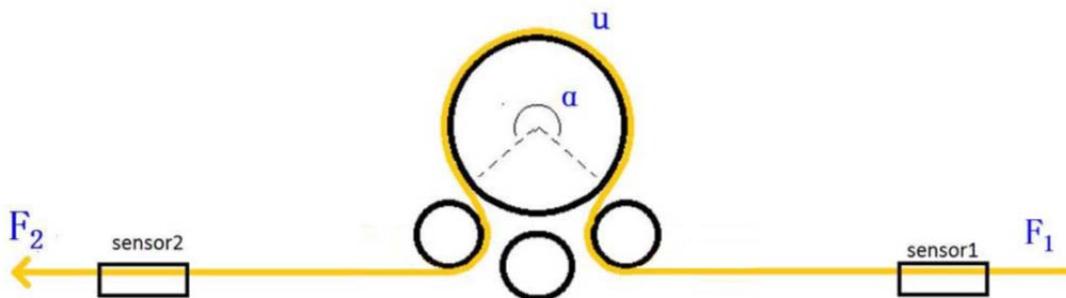


Figure 3-17: Principle of friction measurement with two sensors

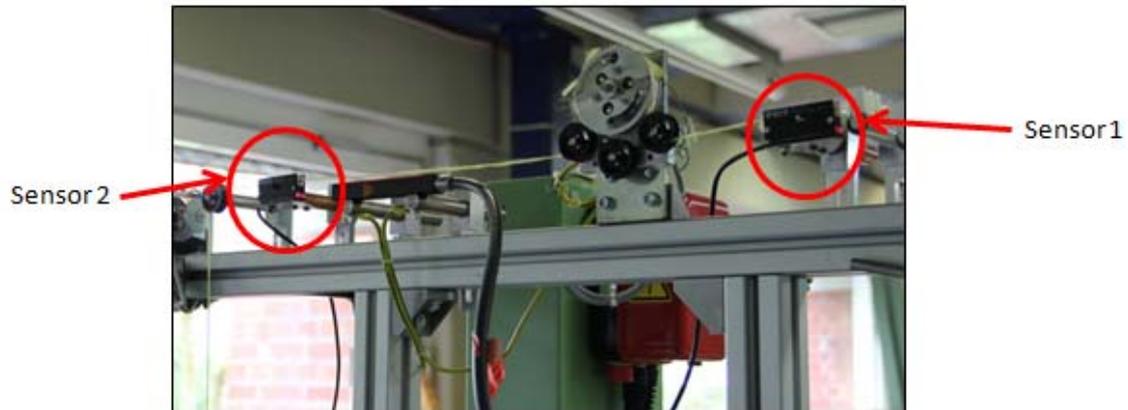


Figure 3-18: Friction measurement device

To determine the friction coefficient, first of all, the linear relationship between force and output voltage of each sensor has to be found and proved. Five different weights were put respectively on both sensors to find the linear relationship. The sensors, which are connected to the program, collected 10 samples at a sample rate of 1000.

Table 3-3: Linear relationship of weight and force

Number	1	2	3	4	5
Weight (g)	5.328	9.508	19.769	39.870	78.209
Force (N)	0.0522	0.0932	0.1937	0.3907	0.7664

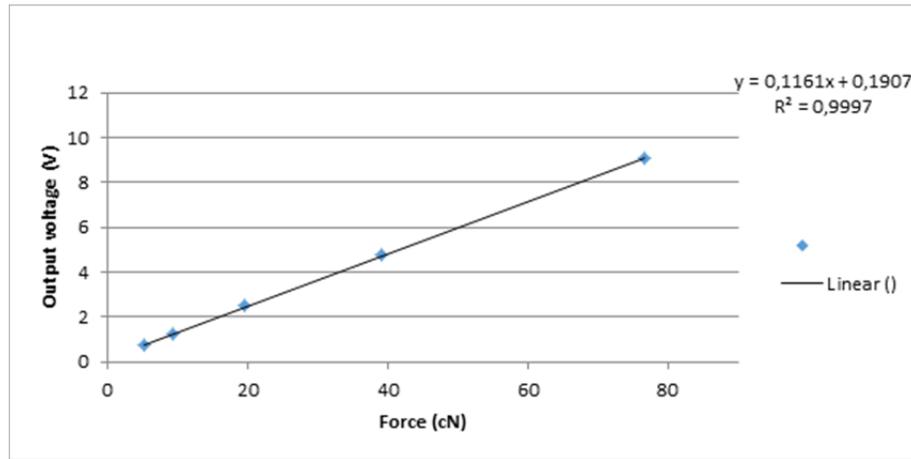


Figure 3-19: Output Sensor 1

The linear relationship between force and output voltage of sensor 1 is

$$V_1 = 0.1907 + 11.61 * F_1 \quad (21)$$

$$F_1 = \frac{V_1 - 0.1907}{11.66} \quad (22)$$

The sensor shows a strong positive regression coefficient of 0.9997.

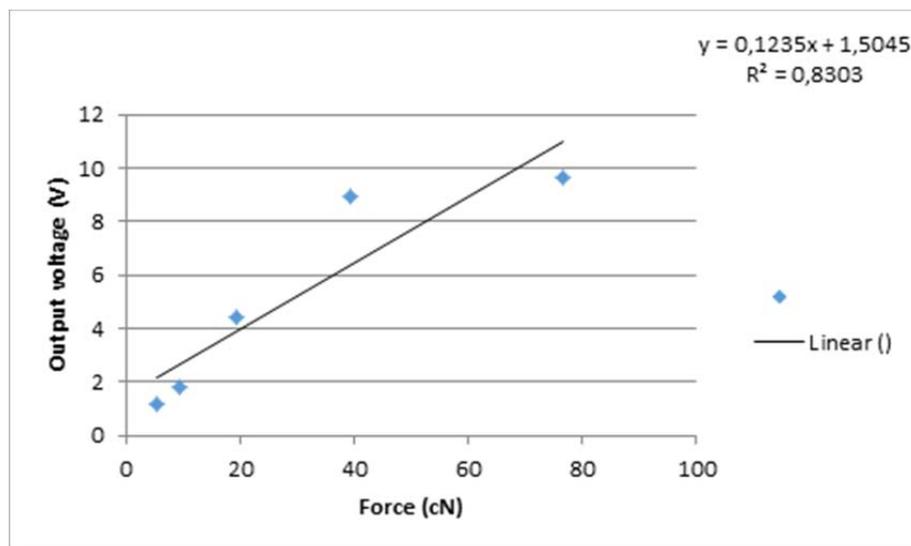


Figure 3-20: Output Sensor 2

The linear relationship between force and output voltage of sensor 2 is:

$$V_2 = -0.2001 + 23.47 * F_2 \quad (23)$$

$$F_2 = \frac{V_2 + 0.2001}{23.47} \quad (24)$$

Also the second sensor shows a strong positive correlation with a regression coefficient of 0.9985.

After calculating and proving the linear relationship of the two sensors, the friction coefficient of the yarns could be measured.

Normally the friction coefficient is tested by rubbing yarn against fabric, but in this case, yarn sample instead of fabrics were used. Therefore yarns were winded onto paper cards, which have the same width like the measurement wheel of the spooling machine to stick onto the wheel surface while the frictional force will not be affected by uncorrelated factors. Table 3-4 presents the surfaces of the different samples.

Table 3-4: Surfaces of the used samples

Number of twists	Handmade cards
52	
103	
202	

The output voltage of the two sensors gives following results:

Table 3-5: Output voltage for the test samples

Yarn	Fabric	V1	V2	sV1	sV2
52	52	0.685138188	8.269455036	0.0627	0.5254
103	103	0.575497035	6.961100691	0.0590	0.4946
202	202	0.628579942	7.314271961	0.0793	0.6221

The force is calculated as mentioned before:

Table 3-6: Calculated force of the test samples

Yarn	Fabric	F1	F2
52	52	0.075438	0.343816
103	103	0.065995	0.288070
202	202	0.070567	0.303118

Out of these results the friction coefficient of each group can be calculated by using the presented formula:

$$\mu = \frac{1}{\theta} (\ln F_2 - \ln F_1) \quad (25)$$

The following Figure presents the results of the coefficients of friction for the three yarns. The yarn with 52 twists show the highest coefficient and resultant of this, the best friction behaviour with a value of 0.48, but there is no significant difference between the yarns visible.

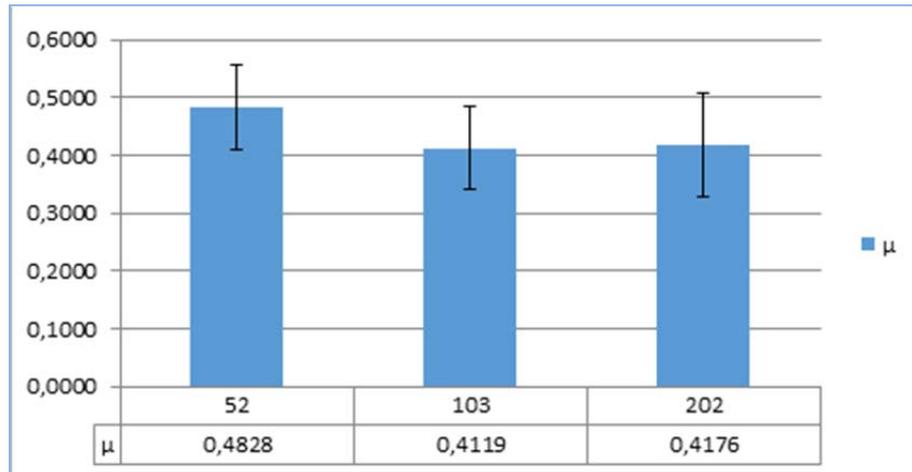


Figure 3-21: Coefficients of friction of the test samples

3.2.3.2 Conclusion

Three yarns with different number of twists were made out of aramid and wool. The yarns have a different amount of winded wool around the aramid thread and the coefficient of friction of the yarns were measured and compared. The values are between 0.4119 for the yarn with 103 twists per meter and 0.4828 for the yarn with 52 twists per meter. Due to the variation in the series, the results are comparable. No significant difference can be seen.

The yarn with 52 twists per meter was chosen, to insert this yarn into a fabric. The goal is to determine the influence of wool inserted in a fabric.

3.3 Setting up of multilayer narrow fabric blends

Like mentioned before, a main problem of flexible stab resistant garments remains to be too heavy to carry, uncomfortable and unsuitable for everyday use. When equipping stab resistant garments with the additional value of resistance, it goes along with decreasing flexibility and weight gain, through the use of additional fabric layers. Therefore considerations were made, how to insert the wool into a woven fabric, which showed a good performance as a layer on the top of a fabric panel like presented before. Due to the amount of material, it was chosen, to weave a narrow fabric in order to have enough fabric material to test it against stabbing in a short machining time. The goal is to develop narrow woven fabrics of aramid, which are intended to improve the puncture-proof characteristics. In view of the improvement, it is analysed whether the combination of wool and aramid can support the stab inhibitory effect.

3.3.1 Materials and methods

Narrow fabrics out of aramid are produced on the narrow weaving machine NFREQ 42 2/84, like presented in Figure 3-22.



Figure 3-22: Narrow weaving machine NFREQ

Narrow fabrics are produced with a warp yarn out of aramid, which is combined in the first series with an aramid weft yarn. To analyse the influence of the wool onto the stab resistance of the narrow fabrics, a second test series with the aramid-wool blended yarn in weft direction is woven. The blended yarn with 52 twists per meter, which was produced and explained in the chapter before, is used here for.

Table 3-7 gives an overview about the parameters of the used yarns.

Table 3-7: Parameter of the used yarns

Test series	Yarn	Textile material	Yarn count (dtex)
	Warp	Twaron Aramid	1680
1	Weft	Twaron aramid	930
2	Weft	Twaron aramid / wool blend	1158

The fabrics are constructed in a basket weave pattern, because in the needle-narrow fabric weaving process, the weft yarn is entered two-ply, why the warp yarn is doubled to produce a round, plain weave-like setting.

Afterwards, the narrow fabrics are tested against stab resistance according to VPAM (Test Standard VPAM KDIW 2004) at a height of 28.4 cm. A panel of four layers of the two different fabrics are tested against stab impact at a height of 28.4cm and compared due to their stab resistance. Three tests are carried out each.

3.3.2 Results

Following the mean values of the two test series are presented in Figure 3-23. The pure aramid fabric is compared to the aramid-wool blend fabric.

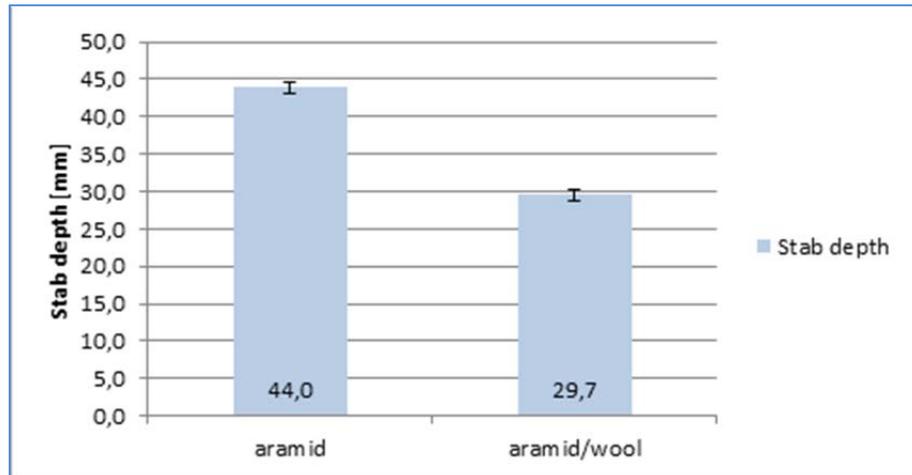


Figure 3-23: Stab depths of the narrow fabrics

The first test series showed a significant influence of the wool onto the stab depth of the fabrics. While the pure aramid fabric is penetrated 44.0mm, the aramid/wool blended fabric presented results of 29.7 mm depth. Figure 3-24 presents the holes in the fabrics after the stabbing. It can be observed, that the yarns in the pure aramid panels are cut, but mostly slide apart, while the yarns in the blended fabric are cut.



Figure 3-24: Aramid and Aramid/wool blend

Like presented in the previous chapters, the yarn sliding apart does not need much energy. For the knife, it is easy to separate the yarns to penetrate the panel. More energy is required to cut the layers than penetrate the layers.

3.3.3 Conclusions

First tests have shown that the wool takes a positive influence on the stab resistance of the test panels. The wool was used just in weft direction in this first series. In future further test series should be performed where the wool yarn is entered in both directions to reinforce the positive effect. Out of this, safety vests could be offered, where fabric layers could be reduced and due to this the comfort for the user will increase.

3.4 Numerical investigations of the penetration through textiles

The analytical methods are very powerful instruments for the investigation of textiles and structures. The meaning of analytical method here is the description of the relations between the parameters in the textile structure and environment and the physical laws with analytical equations. The power of such methods is in their simplicity and clear correlation between the real parameters. This is not the case if some modern methods, like Neuronal Networks or Fuzzy Logic are used. The disadvantage of such analytical methods is that these are in their simplified form not directly adjustable for more complex interactions and any change of geometry of the structure for instance requires the use of new or adapted equations. The Finite Element Method overcome these issues, but requires from other side the understanding, availability and knowledge of several small details about complex software. This part presents an investigation, which is firstly based on analytical methods and then on FEM. It is performed in order to present a methodology for the optimisation of the stab penetration of textiles using pure numerical experiments.

3.4.1 Analytical methods

There are several models for woven textile structures and for their tensile and other mechanical behaviour, but the work of Lomov and Moshkov (Lomov, S. V. and Moshkov, G. V. 1998) presents one very useful for the current model investigation. The model is based on the energy of the system “woven structure – plasticine – stab/cutter”. The authors consider normal interactions of a sharpened rod or a needle with a diameter D , the length of the conically sharpened part L and cone angle β with a pile of N woven layers, as presented on the Figure 3-25.

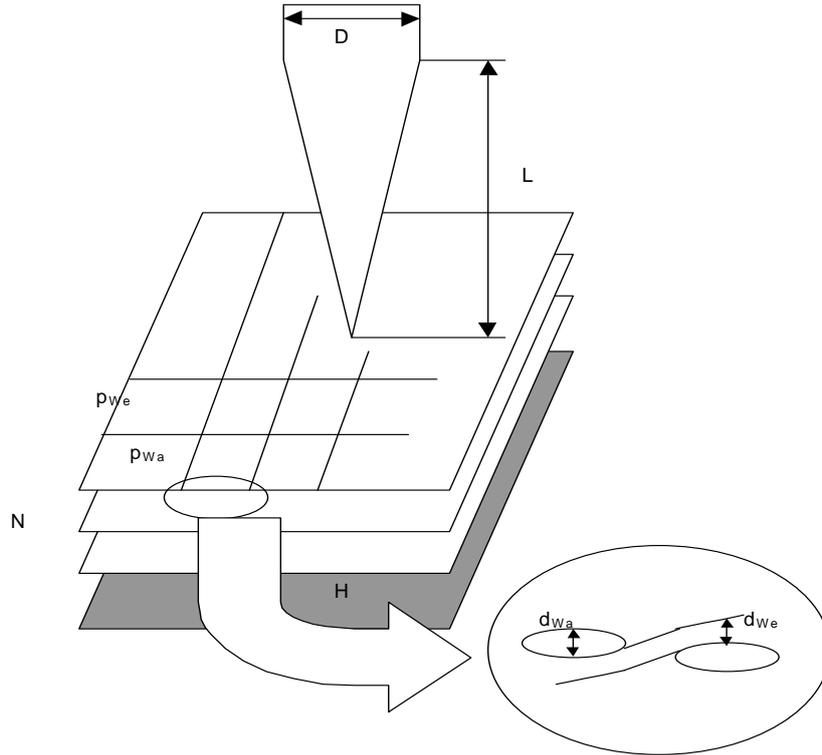


Figure 3-25: Model of the penetration test (Lomov, S. V. and Moshkov, G. V. 1998)

The yarn axis is approximated with polynomial of the power three, which allows its direct integration and differentiation for the computation of the yarn curvature at the contact points of the woven structure. Then, considering the bending and the tension energy of the yarns the yarn tensile force during the penetration can be computed as following ((Lomov 2013)

$$F(d, p_{wa}, p_{we}) = C [4(F_{wa} + F_{we}) + 8\mu Q] (\text{tg}\beta + \mu_m)$$

$$Q = +11\mu \left(\frac{B_{we}^2}{p_{wa}^2} + \frac{B_{wa}^2}{p_{we}^2} \right)$$

$$F_{wa}(p_{we}, p_{wa}) =$$

$$= 144B_{we} \frac{h_{we}^2}{p_{we}^5} \delta x_{wa} + 6B_{wa} \frac{\delta x_{wa}^3}{p_{wa}^3} + 72\mu B_{we} \frac{h_{we}^4}{p_{we}^4} \delta x_{wa} + 11\mu \left(\frac{B_{we}^2}{p_{wa}^2} + \frac{B_{wa}^2}{p_{we}^2} \right)$$

$$F_{we}(p_{we}, p_{wa}) =$$

$$= 144B_{wa} \frac{h_{wa}^2}{p_{we}^5} \delta x_{we} + 6B_{we} \frac{\delta x_{we}^3}{p_{we}^3} + 72\mu B_{wa} \frac{h_{wa}^4}{p_{we}^4} \delta x_{we} + 11\mu \left(\frac{B_{wa}^2}{p_{we}^2} + \frac{B_{we}^2}{p_{wa}^2} \right)$$

Figure 3-26: Computed calculation of the force during the penetration

Here the subscripts W_a and W_e denote the warp and weft yarns, B the bending rigidity, p – the density in pics per dm and μ the friction coefficient.

The resistance of backing is then computed as following

$$F_b(x) = H \left[\pi ((x - Nb)tg\beta)^2 / 4 \right] \quad (26)$$

And the energy equation becomes

$$\int_0^q [F_p(x) + F_b(x)] dx = J \quad (27)$$

Where q is the total penetration of the needle through a set of N layers of the same structure with thickness L . This equation can be solved numerically and the penetration depth is calculated until the state, where the complete energy of the falling cone is dissipated from the bending and friction forces. If the penetration depth is higher than the L , then a complete penetration is stated.

Software implementation of this procedure should be available for older computers (running DOS) and names as program IMPACT, but this was not more executable under the current Windows computers. For performing the calculations, a Matlab Script was written within the FreeMat environment, which is an open source alternative of Matlab®¹.

The calculation as example gives results as following:

¹ Matlab is a trade mark of Math Works Inc

Table 3-8: Listing Output

F =
Warp: 1 1 struct array
Weft: 1 1 struct array
PWa: 100
PWe: 120
fMe: 0.3
f: 0.1
C: 2
H: 0.1
N: 30
res =
NWaRuptured: 2
NWeRuptured: 2
stopped: 1
qTotal: 61.5
qUnderFabric: 55.5

This means, that the cone is stopped, when the penetration depth is 55.5 mm in a fabric set of 30 layers.

The verification of the method is presented to demonstrate the good correlation between the experimental values performed with aramid structures. This proves the general possibility of the method to test and evaluate single structures, varying the friction coefficients, the densities, the cone angle and the energy of the falling cone (Lomov, S. V. and Moshkov, G. V. 1998).

The model was not more used in the current work, because of two issues – the case, where the cone goes through the middle of the yarn and tries to cut it or go through and is not implemented. Such extension with analytical equations would be possible, but it will be again limited to the **normal** penetration and penetrations under another angle will be more complicated for the description. The investigation of such general cases should be possible with some more generalized methods, like the FEM.

3.4.2 FEM Simulation of stab penetration using truss elements

The most simplified and computational effective method for the FEM simulation of the stab penetration of woven fabric is based on the use of truss elements for the yarns in the woven fabrics. The truss elements represent the yarn as a chain of several trusses and their implementation in the software ImpactFEM (Impact 2016) include contact detection capabilities. The disadvantage using trusses, instead of beams, is that the bending moments at the nodes are not transferred (Figure 3-29) because the trusses of the trusses have only the translational degree of freedom. The use of beam elements (with bending and torsion) was not possible in ImpactFEM because these elements were not implemented in the solver.

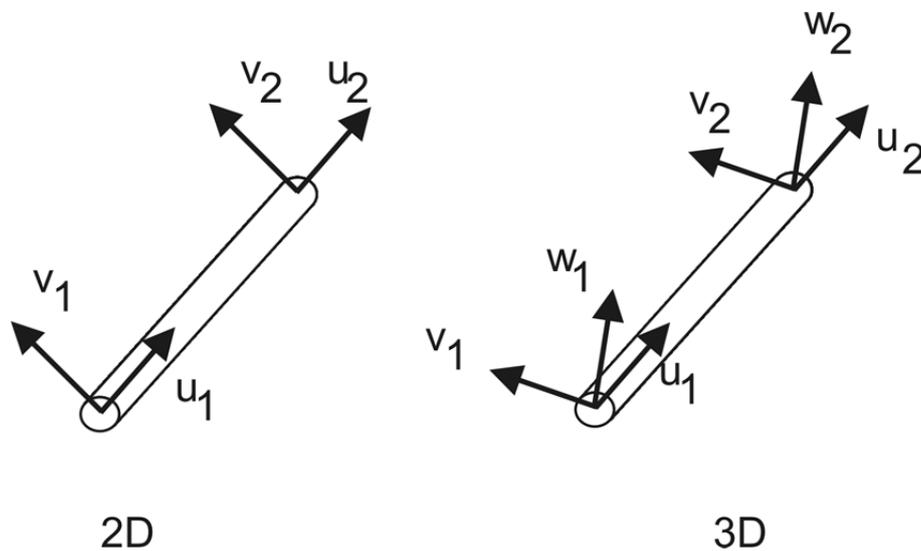


Figure 3-27: Degree of freedom of 2D and 3D truss elements (Veit 2012)

The initial mesh of the woven structure was generated with TexMind Suite (Kyosev 2015), which is able to export direct the elements file into the ImpactFEM format. The penetration element was modelled as well as the triangle structure with trusses as frame structure (Figure 3-28).

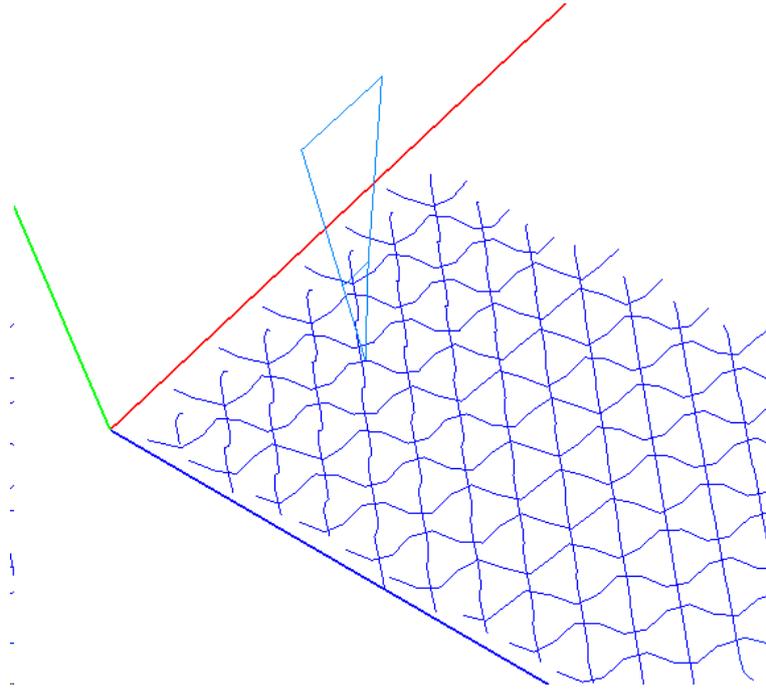


Figure 3-28: Initial mesh for penetration simulation with ImpactFEM, based on trusses

The numerical experiments demonstrated that the model is able to detect the penetration through the structure. One moment of the penetration and the movement of the knife is visualised on the Figure 3-29.

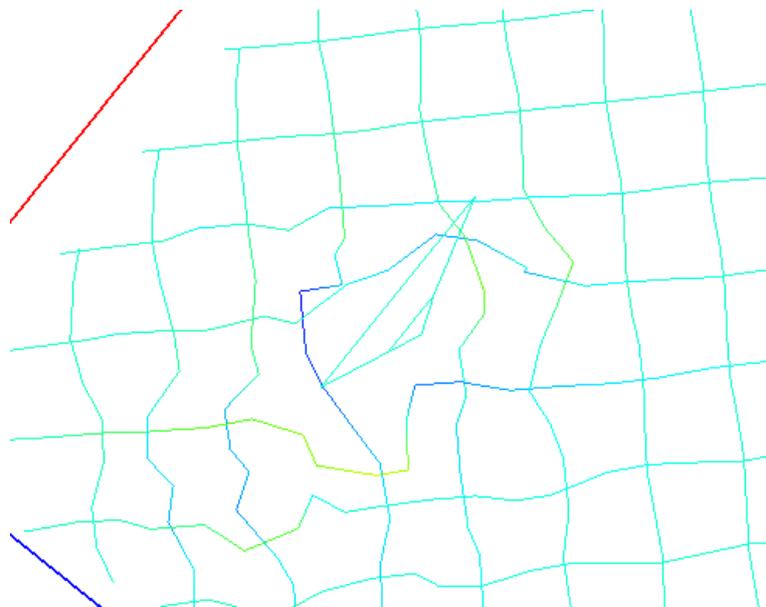


Figure 3-29: Deformed geometry at the beginning of the puncture

The computation time for this simulation is just a few minutes on a standard desktop computer, which is fast enough for performing optimisation tasks, changing different angles and geometries. The main problem of such a model is that the approximation of the yarn cross section with truss elements is not able to consider effects of yarns with other than circular cross sections and the yarn in the aramid woven structures is more close to flat than to circular cross section. Furthermore it is as well recognizable in the Figure 3-31 that the chain of the trusses does not deform smooth like one real yarn, because of the missing bending rigidity in the elements. In this context a more extended model, using shell elements was developed.

3.4.3 FEM Simulation based on shell elements for the yarns

All three parts in this model in terms of rigid knife, woven fabric stack and plasticine are included (Wu et al. 2016). Due to negligible deformation of knife during the penetration, the knife is regarded as a rigid object. The plasticine below the fabric is a typical elastic-plastic material, which plays a role in the test bench similar to human body in realistic stab scenario. Therefore, the plasticine is meshed as solid elements. The yarns are meshed with shell elements, using specially designed script for this (Figure 3-32)

For the sake of simulating the slippage behaviour occurring in the process of penetration, corresponding contact algorithm are also set in this model. The penalty function method is employed in normal direction to determine the force between contact pairs, whereas friction force in tangential direction is modelled by assigning a friction coefficient. There are four friction coefficients: for yarn to yarn, yarn to plasticine, yarn to knife and knife to plasticine, respectively.

During the penetration the boundary conditions at the fabric edges influence significantly the puncture behaviour. In the normal case the fabrics have to be tested in relaxed state, but in the reality the fabrics on the different parts of the body can be loaded uniaxial (stretched) or as well biaxial or under more complex loading.

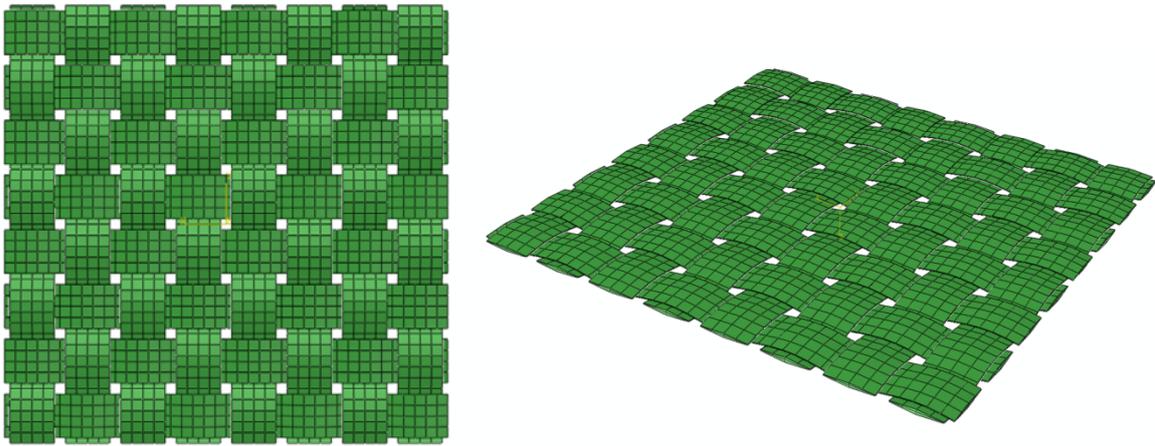


Figure 3-30: The geometry model of a plain woven fabric

The first simulation results demonstrate that the chosen approach – using truss elements with contact and friction capabilities and explicit simulation schema- is able to simulate the puncture behaviour of the fabrics. Due to the low number of elements in the model it is computationally efficient and allows performing several simulation cases per hour, which gives the potential to be used within optimization loops or for performing full sets of designed experiments. The movement of the yarns is similar to the observations in practical tests, but the correct element size has to be investigated, in order to minimize the jumps in the forces and movements of the yarns and resultant of that a nearly smooth behaviour to be observed. The currently used large element size leads to fast and stable contact detection, but leads to large changes of the forces. As the next step the simulation was verified.

Therefore the argument process is organized as following sequence: $A \leq B \leq C \leq D \leq E$, where number A presents the penetration depth - a criterion for the response of knife stabbing. B is the deformation area in the clay and C is the effect of fabric on the deformation area of the clay. D explains the difference between a blunt and a sharp object. Unlike the blunt object puncturing where the primary yarn is pushed by the blunt object, the knife stabbing includes a penetrating process that the sharp tip of knife get through the fabric in an easy manner. However, the increasing body of knife will push the yarn to forming a larger hole for penetrating. Number E defines two different behaviours on the contact between the knife and fabric. The first is the pressure force in the normal direction. The second is exerting force to push yarn aside. The friction force which is determined by the pressure force and friction coefficient between the contact pairs will resist the slippage movement of yarn in fabric, which restrain the hole and consequently larger area is induced, the smaller depth is achieved.

Following first results can be seen in the Figure 3-33 for the first two steps A and B: the penetration depth of two knives with different shape under the same mass and dropping velocity is presented. It is clear that the sharp knife can penetrate deeper, which is explained as the larger area of clay will be deformed in the case of blunt knife. Therefore, the increase of the area of deformed clay is assumed to be benefit for improvement of anti-penetration performance.

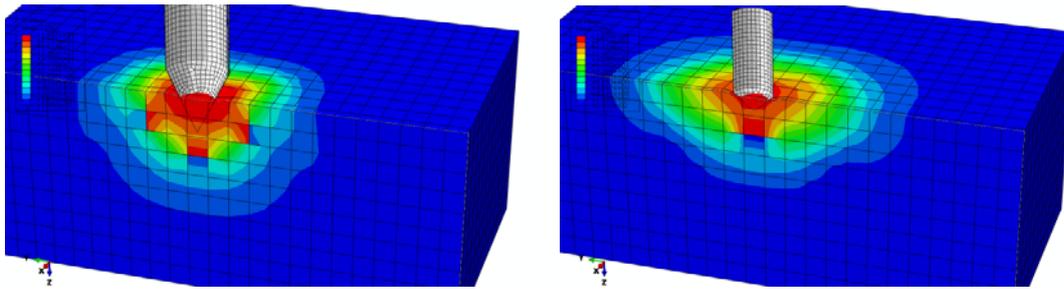
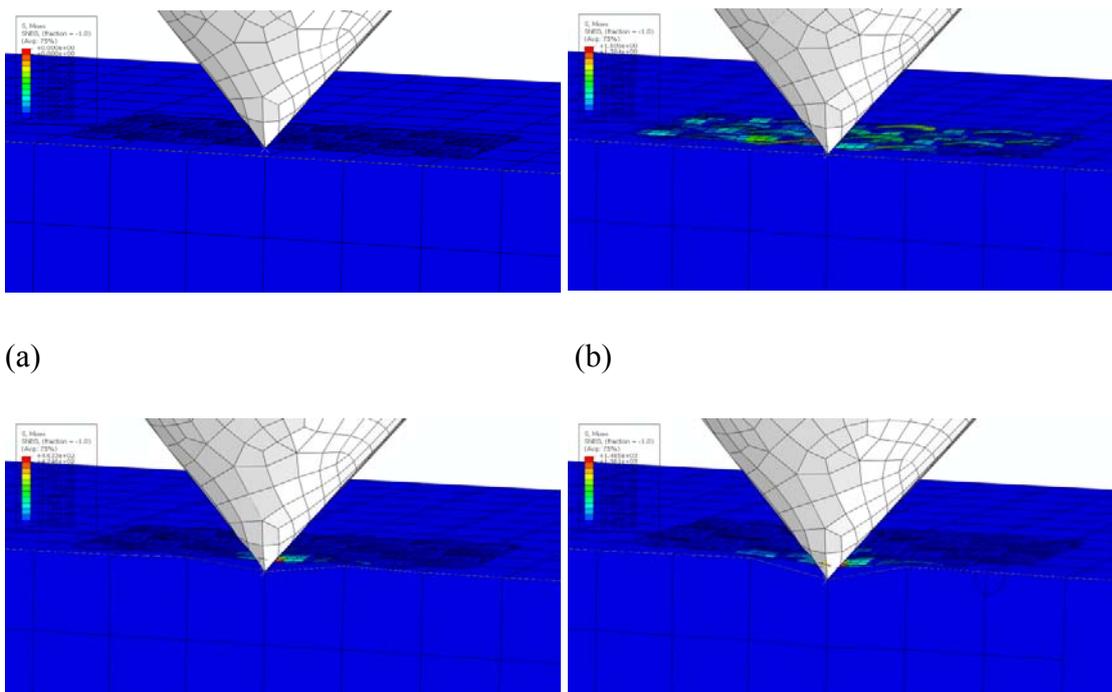


Figure 3-31: The penetration depth into the clay by different knife shapes (left: sharp, right: blunt)

In part C, a whole simulation model consisting of clay, knife and a single layer of fabric was established in the finite element code ABAQUS to investigate the influence of fabric during the penetration process. (Hibbett et al. 1998) Like presented in Figure 3-31, the geometric model of the plain woven fabric was simulated. For presenting the flat shape of yarn in the fabric, the centreline of yarn is calculated in the Matlab and the four shell elements are employed to model the cross-section of the yarn. (Grant et al. 2008)



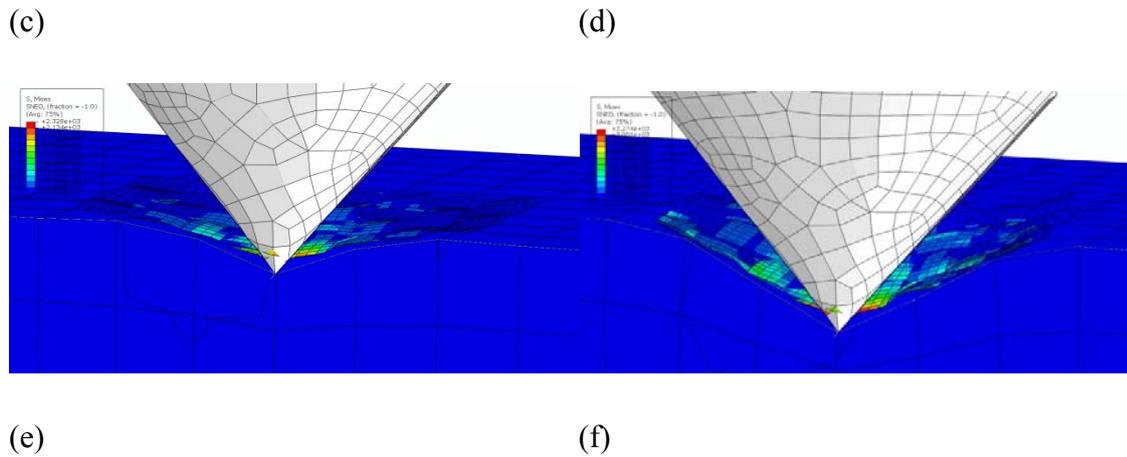


Figure 3-32: Penetration process

The figure 3-32 presents the simulation of the penetrating process of a knife. In the model, the clay is placed on the bottom. A plain woven fabric covers on the top of clay. A knife with a specific mass drops down to stab into the fabric through the fabric. With the penetration of the knife, the fabric was pushed to the clay and the edges of fabric lifted upward due to its bending stiffness, which was similar to the experimental results. A large space is observed between the knife and the fabric, which indicates that the clay is pushed by the fabric instead of the knife. Thus, the deformation area of clay increases due to the existence of the fabric.

For further investigations, the effect of the fabric on the penetration performance, the structural deformation of the woven fabric at yarn scale, is depicted in the figure 3-33.

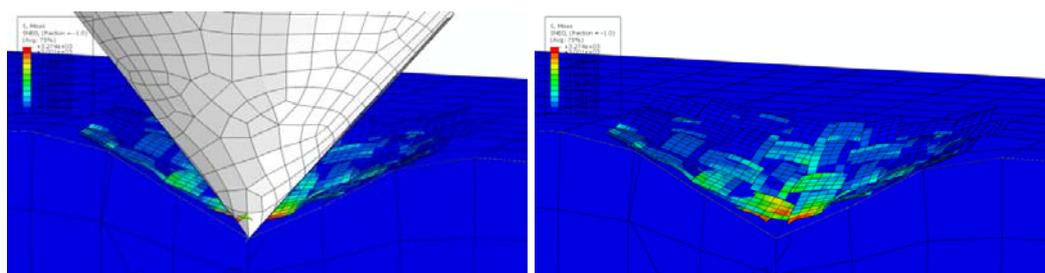


Figure 3-33: The deformation of fabric during the penetration process

The Figure 3-34 shows the deformation of woven fabric during the penetrating process.

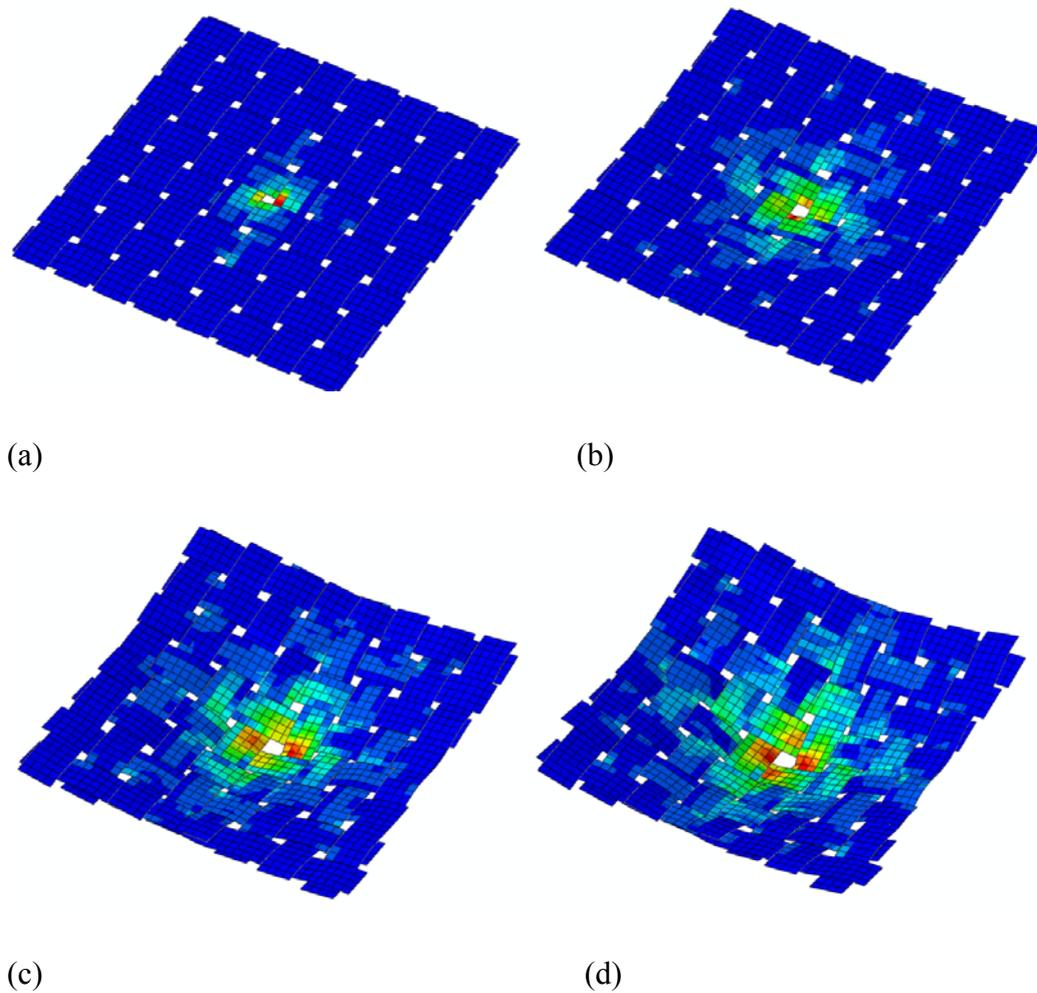
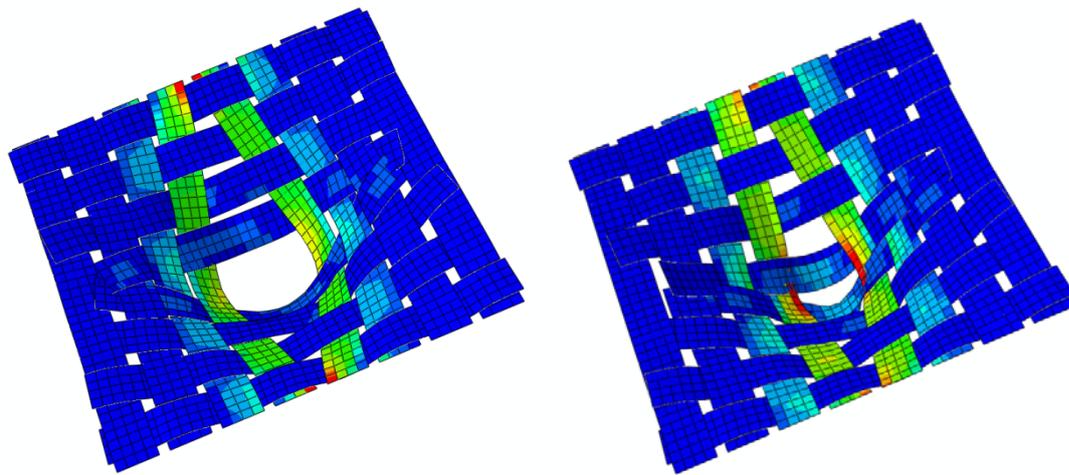


Figure 3-34: The structural deformation of the fabric and slippage of the yarn

Due to the sharp tip of knife, the contact between the knife and the fabric occurs in a small area and the tip of knife goes through the fabric. Then, the knife with an increasing body size pushes the yarn side to generate a hole. Obviously, the knife is easier to impale the woven fabric if the hole is easier to be formed.

The following numerical results reveal the effect of friction coefficient on the slippage of yarn, described in number D and E. The contact between yarns has different friction coefficients. The results also shows that the high friction coefficient restrain the hole forming.



(a) friction coefficient: 0.3

(b) friction coefficient: 0.8

Figure 3-35: The structural deformation of fabric and slippage of yarn under different friction coefficient

3.4.4 Conclusions

The (semi-) analytical method of Lomov and Moskov allows first quick analysis of a given structure about its penetration resistance and can be used for the initial design of the fabrics.

For the extended optimisation a FEM Model is required. The tested truss element model shows principle possibility for the use in penetration simulation tests, but would be more powerful and more accurate if beam instead of truss elements can be used and if these beam elements could have some variable, or at least flat cross section.

The most accurate would be a simulation with solid elements for the yarns, but this will be as well connected with the larger computational time, so it was not considered in this work.

As very good compromise between the computational time and accuracy, the model based on shell elements in ABAQUS seems to be the best. It allows definitions of different layers and with different friction coefficients and presents the simulation close to the reality.

CONCLUSIONS AND FUTURE WORK

4 Conclusions

The research goal of this thesis was to examine various aramid fabrics with regard to their stabbing behaviour and to find influencing factors to this. An attack can only be inhibited, but an injury cannot be completely prevented. The goal is always to absorb as much energy as possible, so that the penetration is thus reduced and the risk of injury decreases. The stab mechanism is a complex and variable process. The review showed the demand on research in this area, because the most solutions involve hard body armour parts in combination with fibrous materials. This material combinations show many disadvantages with regards to the high weight and the missing flexibility. Other researchers also recommend textile solutions, (Horsfall 2012) because they are flexible and in the field of ballistic panels they are already used. The investigations carried out within this thesis are done to contribute to the development of pure textile stab-resistant panels. Therefore the interdependencies between the physical properties of the material but also the mechanism during a stab attack have to be recognized, to develop higher protection levels. It was shown, that the multitude of factors causes the problem to define a level of protection. For example, the high kinetic energies are not always critical. A needle bends for example during a fast penetration while it perforates the fabric at a slow penetration level.

General investigations were done to analyse the test parameters, which are defined in the test standard but also this one, which are missing. It was shown, that the blade can be used several times, without tearing and resultant of this, influencing the test results. The measurement results did not change significantly after a test series of thirty tests, why every knife was used for a maximum ten times in all test series. Also the not defined pretension during the stab tests was analysed. It was demonstrated, that the pretension has no influence on the stab depth but on the trauma size and volume. Even if the stab depth is not significant different, a pretension on the test samples prevents an additional trauma effect. In this context a new method to determine the stab depth was developed, which allows the analysis of the depth of the knife during the impact, but additional to this, the trauma volume and depth and the deformed fabric layer was fixed stable for further analyses like the measurement or the comparison with simulation results. Also the sample size is not defined in the standard for fabric samples, because just ready-made safety vests are tested. It was found that there are no differences between sample sizes of 15 by 15cm up to 30 by 30cm. In order to obtain comparable and

reproducible results, the number of measurements was fixed to three and the sample size to 20 by 20 cm.

Based on the experiments carried out it can be said for all fabric types, that there is a direct correlation between the number of tested layers and their stab inhibitory effect. With increasing number of layers, the penetration depth of the blade will decrease. However, since it does not make sense in terms of wearing comfort and the flexibility, to increase the number of layers of fabric for stab resistant garments to an unlimited level, further properties which lead to improved puncture resistance have to be analysed and taken into account.

The influence of impact energy onto the stab depths was analysed, why the stab heights were varied between 4.5 joules and 9 joules, to find out differences between the patterns. It can be said, that the stab depths increase linear to the increasing impact energies and also it is noticeable that the number of layers has a higher influence when using lower impact energies.

Next step was to analyse the influence of the number of layers. For all different fabric types, panels between six and ten layers were used, but it can be said, that the number of layers gives no significant trends of stab depths. In practice, panels out of 35-40 layers are taken to give a sufficient protection against injuries caused by a stab attack, what could be a reason for the similar results of the panels.

A further study was carried out to evaluate the influence of the construction parameters of the different fabrics, like mass per unit area and thickness. A comparison of the plain weave fabrics presented, that the stab depth decreases with increasing of the mass per unit area. Interestingly, the two twill fabrics show similar results, so that depending on the number of layers sometimes the lighter performs better, sometimes the heavier and thicker twill fabric was better. An identical behaviour during the stabbing process can be noticed for both fabrics. Only partly individual filaments are cut in all fabrics while the mechanisms of displacement could be seen, where the blade causes larger holes. The twill fabrics show much more displacement due to the loose structure of the fabrics and have a poor stitch inhibitory effect. They allow a relatively high penetration depth and also strong displacement effects in the puncture area of the blade.

In the next series of trials, the influence of pattern was analysed of the different fabric types with the same mass per unit area weight. Based on the performed tests it can be assumed that the construction parameters of aramid fabrics present a significant influence on the stab

inhibitory effect. The individual fabric types allow very different penetration depths of the blade. All three plain weave structures show a better application possibility than the twill pattern and the heavier fabrics showed a better stab resistance. The two different twills do not significantly show differences in the measured penetration depth.

Following, the properties, which influence the yarn migration were analysed and compared, to define how to measure the slippage of the yarns but also the frictional behaviour. Therefore, the frictional behaviour of different fabrics was tested to find out interdependencies between the frictional characteristics of different armour materials and the stabbing performance. The static and dynamic coefficients of friction were determined. To compare the frictional behaviour of aramid fabrics with other materials, also the plain weave wool, which was also used in previous test series, was tested. The weft directions show higher tendencies of friction coefficients than the warp directions for both series. Denser fabrics having finer threads and more threads per cm showed a lower resistance against friction thus the fabric has a more even surface.

Also the kind of fibre material influences the frictional behaviour why tests aramid against wool were carried out. Therefore the static and kinetic coefficients of friction of the different aramid fabrics and the wool fabric were compared with each other for all combinations of warp and weft directions. In total, the twill fabrics showed the highest influence of the wool onto the frictional behaviour of aramid fabrics. The values were much higher than the plain weave fabric results. The comparison of the weave direction showed the highest influence of the wool onto the warp/weft and the weft/weft combination.

To determine the influence of the effect of seam slippage, the different woven aramid structures were also tested against shift by determining the seam slippage and the interdependence between the yarn slippage and the stab penetration was tested. Therefore the opening force was measured at different seam openings and these results have been compared to the stab resistance of 6 and 8 layers panels. An interdependence between the seam slippage behaviour and the stab penetration depth results could be seen. Due to the migration of the aramid yarns in the fabrics, the relationship between the decreasing of the force to open a seam and worse results of the stab depth could be seen. Understanding the phenomenon of yarn sliding will help to forecast the fabric properties for safety garments and other applications.

The slippage of the yarns was also tested by the yarn pull-out method which is a practical method to investigate the frictional properties of a fabric like the fabric's deformations and its ability to absorb energy.

To prevent the extensional stress in the fabric area, a new test method was found, where the fabric is clamped on the top and the yarn, which will be pulled-out, is cut out. This yarn is clamped in the bottom clamp.

To find out if there are influences on the pull-out behaviour for the different fabric constructions, two different fabrics were compared with each other. Results of the plain weave structures showed that the pull-out forces of the weft yarns were higher than the values for pulling-out the warp yarns. The pull-out forces in warp and weft direction of twill pattern were comparable. They showed the same behaviour in the force, which is required to pull out one thread; just the displacement moment varied.

Based on the tests carried out it can be hypothesized that the constructional characteristics and the resulting fabric properties of aramids exercise a significant influence on the effect of the stab resistance behaviour. The results showed that yarn pull-out force depends on pattern and for plain weave fabrics also on the yarn direction in the fabric. In general, the pull-out forces of tight plain fabrics were higher than those of loose fabrics like twill fabrics. Also the weft directional yarn pull-out forces of twill fabrics were slightly higher than those of warp directional yarn pull-out forces. Plain weave fabrics show this effect much stronger; the weft directional pull-out force was much higher than the warp directional force. The results confirm the behaviour of the different fabric types on penetration. This is reflected both in the pull-out forces where the twill give significantly lower results, and in the penetration, where the easier thread displacement permits a deeper penetration.

An important point is the need to stabilize the fabric to prevent the displacement of the threads. The friction tests showed that the wool's surface interacts with the smooth surface of the aramid layer during the penetration process. Therefore tests were carried out by inserting a wool layer on the surface of aramid panels and to increase the protection level. The tests showed that the placement of layer of wool fabric on the top of the aramid panel changes the penetration behaviour. It could be seen in two different analyses. The influence of wool has been investigated first by an optical observation of the fabric surface. A high-speed camera picture sequence presented the penetration moment, when the blade penetrated the fabric.

Here general differences between the panels with and without wool could be recognized, where wool prevented the yarn sliding of the below aramid layer. Additional to that, the stab opening in the fabrics were measured for all fabric kits. Measuring the stab depth, all fabrics showed a positive effect, when a layer of wool was lying on the aramid panel. The twill fabrics showed the highest influence of inserting wool into the panels.

So it seems that the insertion of wool is able to contribute to a stabilization of the aramid fabric, where it reduces the sliding apart of the filaments during the stab penetration and causes a cut, which absorbs more energy. Furthermore, it can be assumed that an improvement in the penetration depth of the blade through the use of wool is achievable most in those fabrics where the threads move very easily and can be displaced, like it can be seen in the twill structures. This improvement is also strongest when the wool fabric is used as an outer protective layer on the aramid layers.

The investigation demonstrates that inserting wool into a protection panel can lead to the achieving of acceptable stab depth values with fewer layers. This leads to weight reduction and improved wear comfort of the soft panels.

It was shown, that laying a layer of wool onto the stab resistant panel, a positive influence onto the stab resistance is given. But this was just a layer of wool on top; it was not inserted directly into the panel. Therefore the next step was to insert the wool into the yarn to increase the friction coefficient of the fabric itself. The used method was to blend the aramid yarn with a wool yarn into a core yarn. This was done with a hollow spindle spinning machine, where the yarn was composed of core yarn and cover yarn. To find the best combination of aramid and wool blend hollow spindle yarns for the highest friction coefficient, three yarns with different twists per meter between 50 and 200 planned twists per meter were produced.

Afterwards the friction of the yarns were measured and compared. The yarn with 52 twists showed the highest coefficient and resultant of this the best friction behaviour but due to the variation in the results, no significant differences between the yarns were visible.

To predict the stabbing behaviour of textiles the resistance mechanism of woven fabric against the falling knife and its influence factors were investigated by numerical and experimental methods. Simulation at different scales using explicit FEM was employed in order to select suitable methods for practical optimisation of the protective textile systems. The results also shows that the high friction coefficient restrain the hole forming. Additional

to these simulations, the penetration depth of knife in plasticine has to be compared with the experimental data to verify the validity of the numerical models. The resistance mechanism of woven fabric against the falling knife also has to be discussed in detail by analysing the slippage distance between yarns and corresponding absorption energy. Finally, the values for the penetration depth of knife in various protection textile configurations should be compared to evaluate the role of the number of layers in a woven fabric panel.

5 Future work

There exists a lot of knowledge that can be applied to stab resistant armour. The scope of this research programme was to analyse the main factors, which influence the stabbing performance of stab resistant textiles and improve some testing methods, to give a better understanding of the interactions between the fabric and the knife during the impact. Due to the fact, that there are many test methods to apply statements about the friction behaviour of textiles, these methods should be compared to find interdependencies between them and the stabbing performance of textiles.

The fabric structures, which had the highest stitch inhibiting effect in this work, should be taken for further research to find out whether they are suitable for the actual application in body protective equipment.

Also improvements made by material combinations that increase the stab resistance and thus enabling an improved comfort in form of using less fabric layers were presented. Future work should analyse, how to insert these fabric layers into a panel. Also the best combination of protection level and comfort performance has to be found, in order to make it lighter and comfortable.

Another point was the development of blended yarns out of aramid and wool. Further work should be, to weave different structures out of them to compare the stab performance of these material combinations and find out, which one would be the best.

The simulation of the stabbing interaction has to be improved, to make realistic forecasts of the resistance mechanism of woven fabric against the falling knife and its influence factors. Simulation at different scales using explicit FEM has to be verified with practical results in order to select suitable results for practical optimisation of the protective textile systems. These could be used for real simulation of the puncture behaviour of aramid or other fabrics with different knife shapes. The models should be verified with experiment. Due to the limited time this was not possible. Different knife orientations and geometries and layer number should be as well tested.

APPENDIX

6 Publication bibliography

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7 Appendix

7.1 Mean values of stab depths for all fabrics

	Joule	6 layers	7 layers	8 layers	9 layers	10 layers	6 layers	7 layers	8 layers	9 layers	10 layers
		Mean values					Standard deviation				
P61	4.5 Joule	24.7	19.7	20.0	19.3	18.7	0.5	1.7	1.6	0.9	1.2
	6.0 Joule	39.7	35.0	35.7	32.0	31.3	1.2	1.6	0.5	2.2	2.6
	7.5 Joule	48.7	43.7	45.3	40.7	40.3	0.9	1.7	3.3	2.5	1.7
	9.0 Joule	52.0	50.3	50.3	48.0	49.3	2.4	1.9	0.9	2.4	1.7
P170	4.5 Joule	19.3	18.7	14.0	12.7	13.3	1.9	0.9	2.2	2.5	1.2
	6.0 Joule	34.3	32.7	27.7	27.3	24.7	0.9	1.7	1.2	1.7	0.5
	7.5 Joule	42.7	39.0	36.3	36.0	34.0	1.7	2.2	1.9	3.3	3.7
	9.0 Joule	44.3	43.7	42.3	40.3	42.7	1.7	1.7	0.9	1.7	2.1
T170	4.5 Joule	22.7	24.3	24.7	25.3	20.7	2.1	2.6	0.9	1.2	0.9
	6.0 Joule	36.3	37.7	35.7	32.0	32.0	2.6	0.9	1.2	2.2	2.2
	7.5 Joule	45.7	43.3	43.3	40.3	39.7	2.9	1.9	2.9	2.6	1.2
	9.0 Joule	50.3	49.7	47.3	44.7	46.3	2.5	1.7	3.3	3.1	0.5
P230	4.5 Joule	18.0	16.3	14.7	14.7	13.7	1.6	1.2	1.2	1.2	1.2
	6.0 Joule	31.3	28.7	24.3	24.3	21.0	2.4	1.2	2.4	1.2	1.4
	7.5 Joule	33.7	33.7	31.7	30.7	30.3	2.6	1.7	1.2	0.5	1.7
	9.0 Joule	39.3	36.3	36.0	35.0	31.0	1.2	2.6	2.2	1.4	1.4
T230	4.5 Joule	14.7	15.7	13.0	14.7	14.7	1.9	1.2	1.6	0.9	0.5
	6.0 Joule	37.3	34.3	36.3	33.3	36.3	1.7	2.6	1.2	2.1	2.1
	7.5 Joule	43.7	45.3	41.7	38.7	40.7	2.6	2.1	0.9	2.1	0.5
	9.0 Joule	52.3	52.0	50.3	50.0	48.7	1.7	2.2	2.4	2.2	2.1

7.2 P170

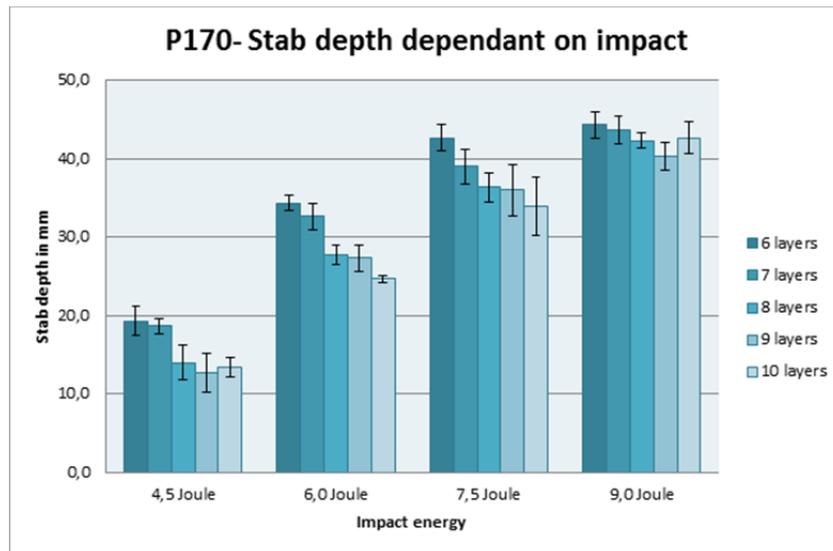


Figure 7-1: P170 - Stab depth dependant on impact

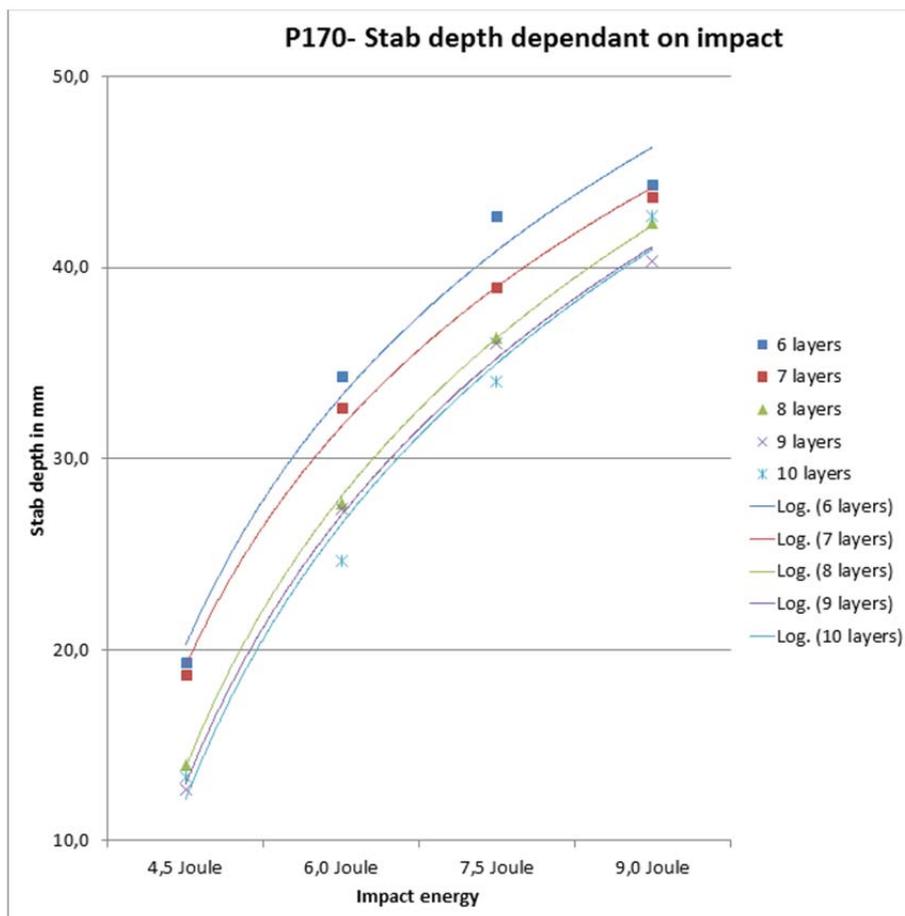


Figure 7-2: P170- Logarithmic curves

7.3 P230

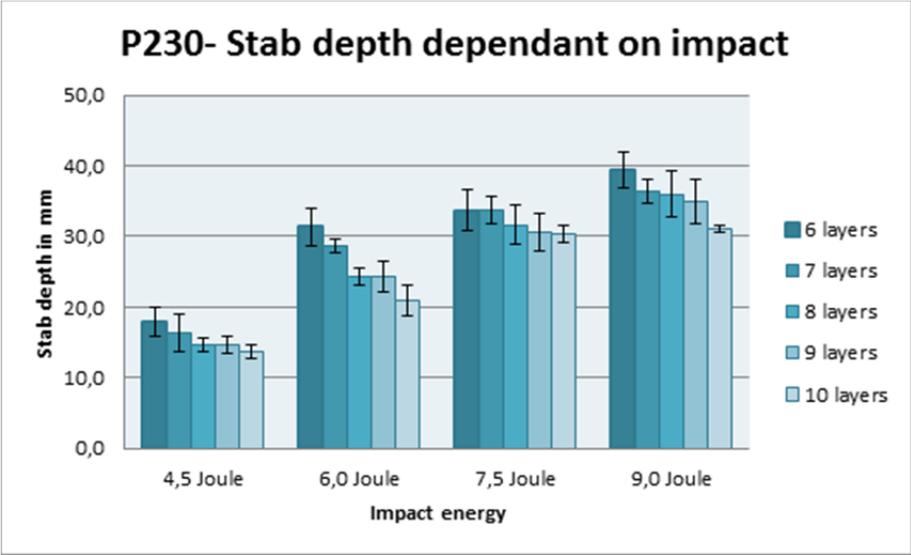


Figure 7-3: P230 - Stab depth dependant on impact

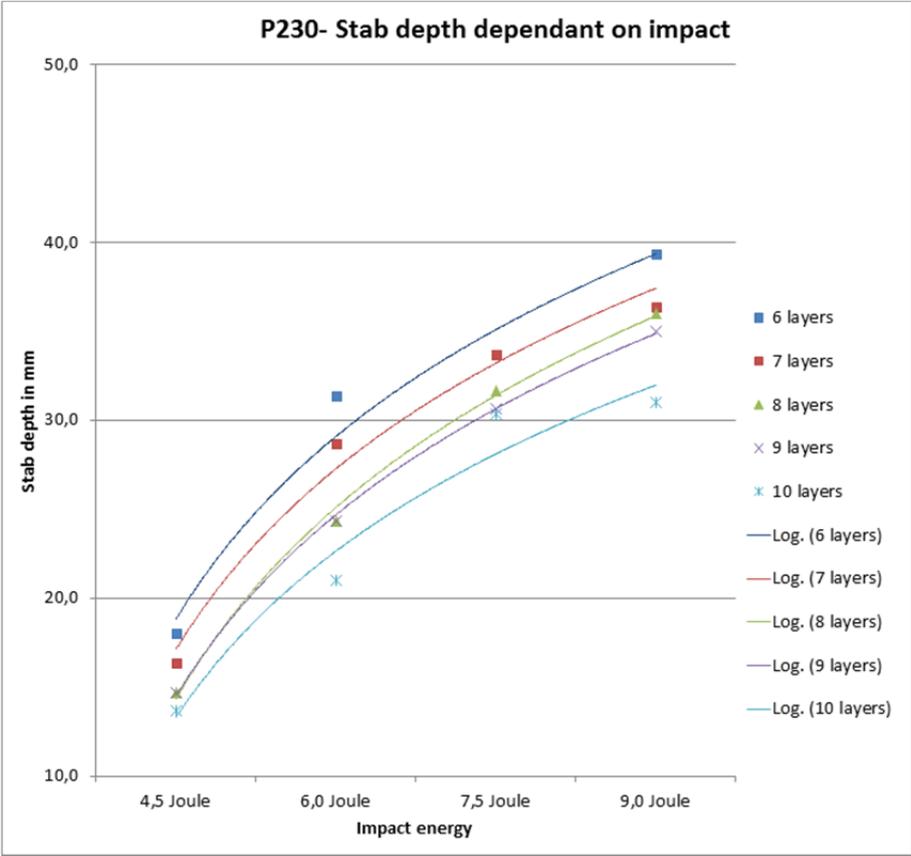


Figure 7-4: P230- Logarithmic curves

7.4 T170

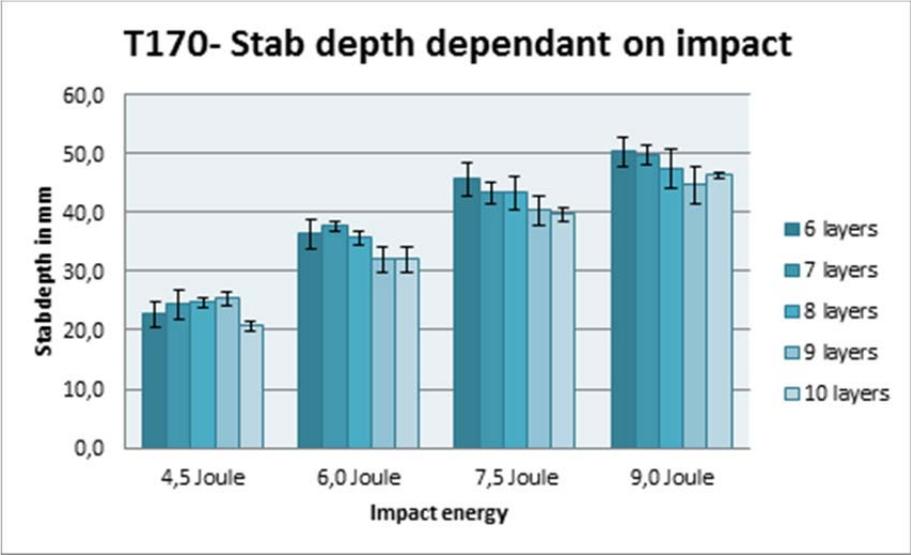


Figure 7-5: T170 - Stab depth dependant on impact

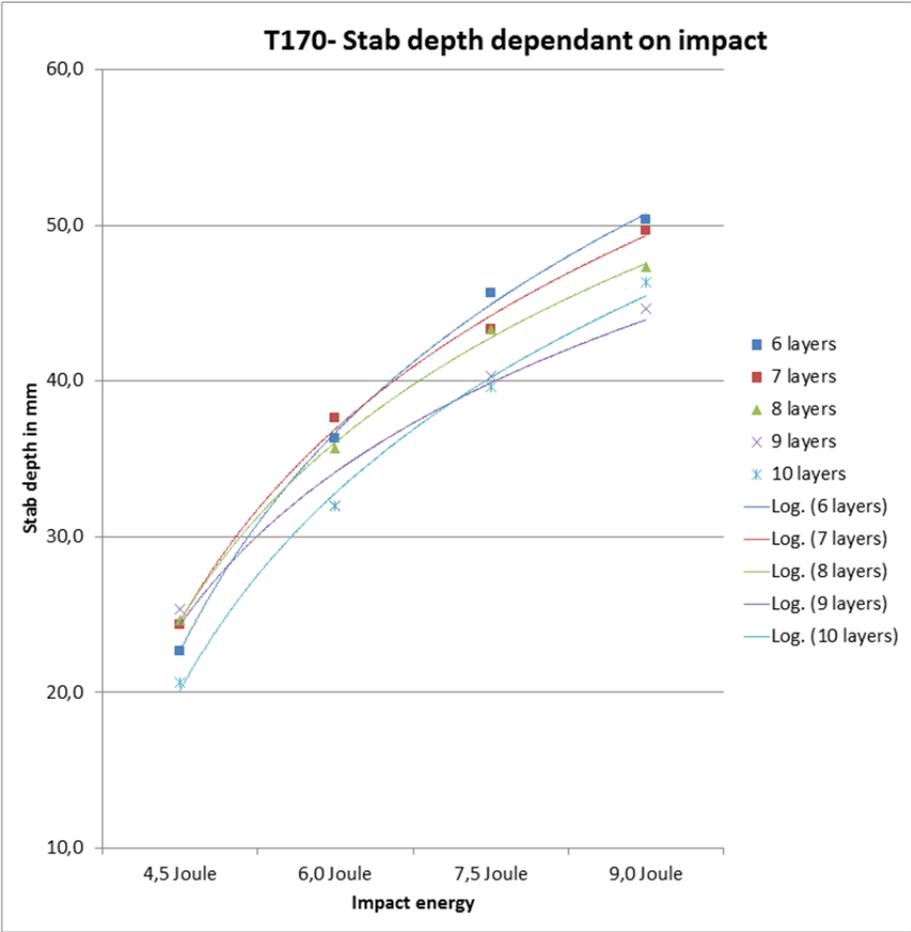


Figure 7-6: T170- Logarithmic curves

7.5 T230

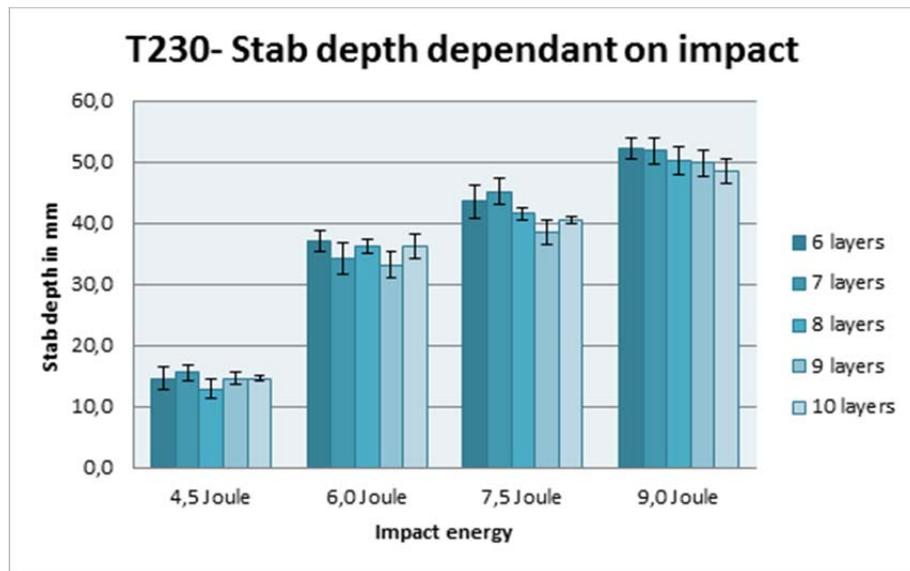


Figure 7-7:T230 - Stab depth dependant on impact

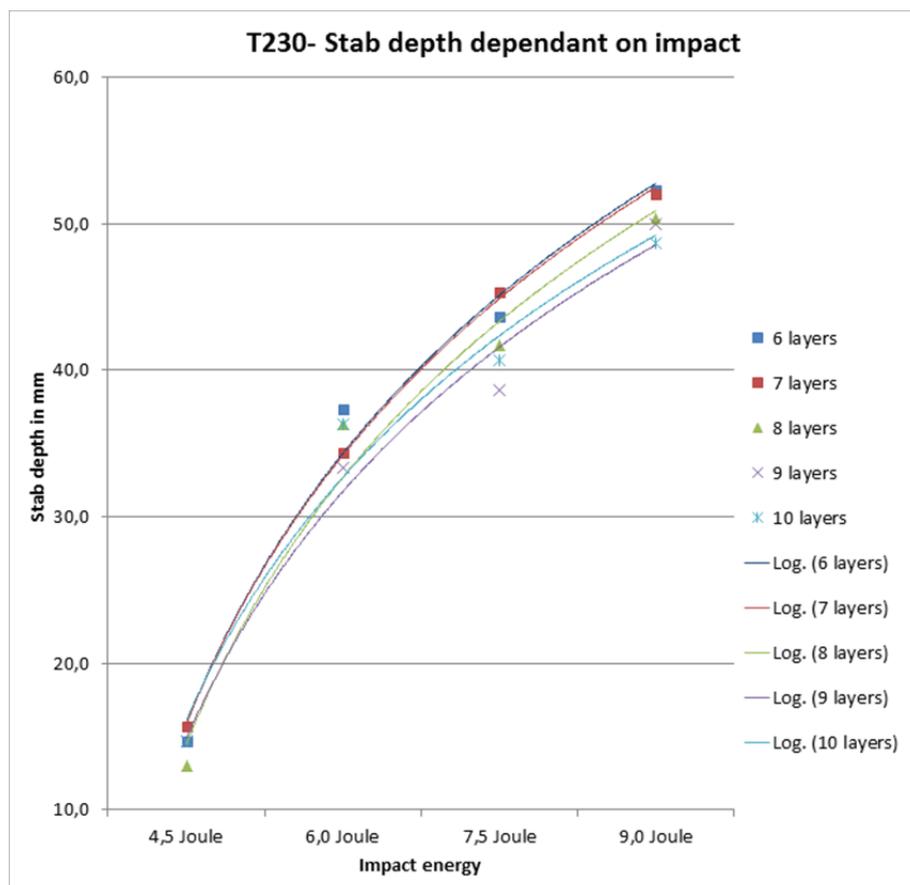


Figure 7-8: T230- Logarithmic curves