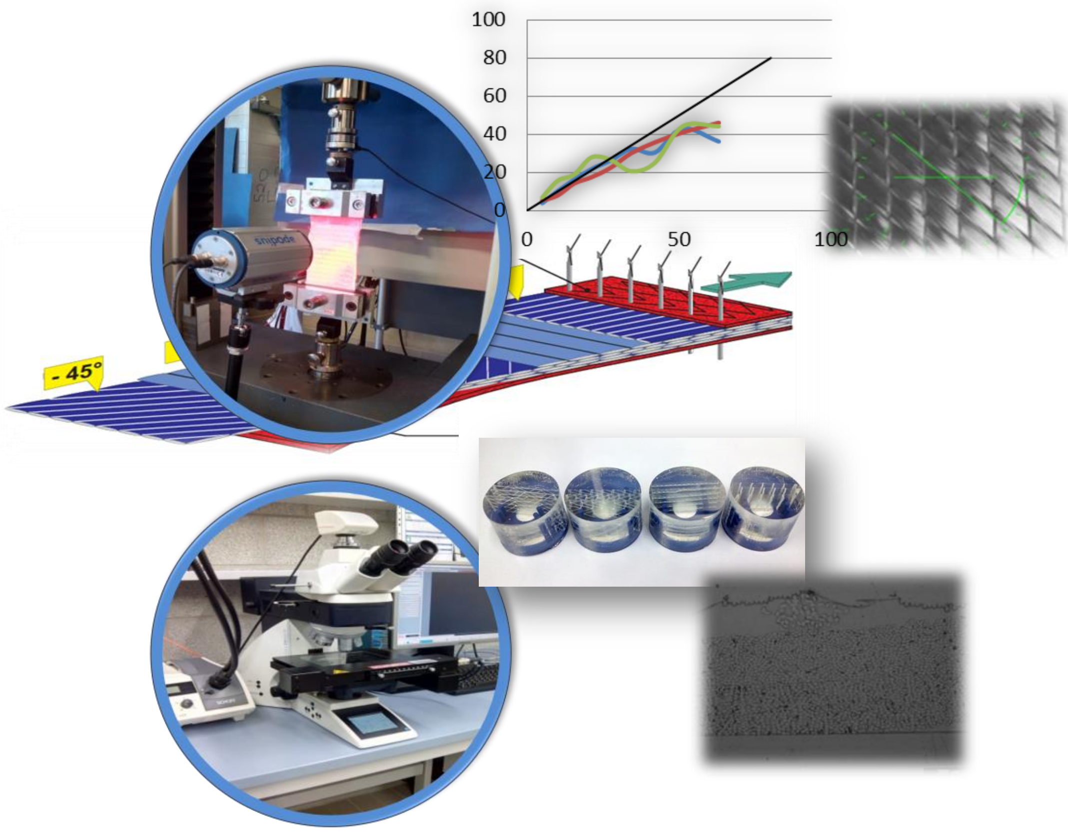

2015

Bachelor Thesis

Analysis of mechanical and geometrical properties of multiaxial non-crimp fabrics

Patricia Domingo Bartolomé

Institut für Textiltechnik of RWTH Aachen University

Univ.-Prof. Prof. h.c. (Moscow State Univ.)
Dr.-Ing. Dipl.-Wirt. Ing. Thomas Gries

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Presented as:	Bachelor Thesis
by:	Patricia Domingo
Matr.-No.	350525
Supervisor:	Dipl.-Ing. Dipl.-Wirt. Ing. Marcel Haeske

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Kurzfassung

Die Industrie der Gelege für Verstärkungsmaterialien hat sich in den letzten Jahren entwickelt. Multiaxialgelege können für viele verschiedene Anwendungen eingesetzt werden - insbesondere dort, wo hohe Festigkeiten und Steifigkeiten erforderlich sind. Durch Änderungen der Parameter der Produktion wie Kettfadenspannung, Bindungstyp und Stichweite können spezifischen Eigenschaften eingestellt werden.

Das Ziel dieser Arbeit ist die Untersuchung der Eigenschaftsänderungen bei Änderung der Parameter. Zu diesem Zweck werden zwei Methoden anwendet; Mikroskopie untersuchungen und Schrägzugversuche. Durch eine Analyse der Grenzen werden die Eigenschaften der einzelnen Anwendungen bestimmt.

Abstract

The industry of non-crimp fabric for reinforcement materials is developing in the last years. Multiaxial fabrics can be used for many different applications- especially where high strength and stiffness are required. Changes in the parameters of production as warp yarn tension, pattern type and stitch length are the key to obtain specific properties.

The aim of this thesis is to determine the differences between these changes. For this purpose two methods will be used: Microscopy and bias extension test in order to analyze the better boundary to obtain the properties of each application.

TRABAJOS DE FIN DE GRADO / FIN DE MÁSTER

Escuela de Ingeniería y Arquitectura
Universidad Zaragoza

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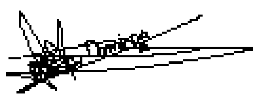

Fdo: PATRICIA DOMINGO BARTOLOME

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Acronyms and Symbols

CNC	Computerized numerical control
EBC	Electronic Beam Control
HSV	High Speed Video Camera
ITA	Institut für Textiltechnik der RWTH Aachen University
max	Maximun warp let-off adjustment (low yarn tension)
min	Minimum warp let-off adjustment (high yarn tension)
N	Newton
NCF	Non-crimp fabric
PA	Polyamides
PE	Polyethylene
PES	Polyester
PET	Polyester (polyethlene terephthalate)
rack	Unit used for warp let-off calculations in warp knitting machines, 1 rack equals 480 revolutions or stitch courses
RWTH	Rheinisch-Westfälische Technische Hochschule Aachen
rpm	Revolutions per minute [min^{-1}]
WKM	Warp knitting machine

γ	shear angle [^{o}]
b_{BE}	sample width [mm]
l_{BE}	Sample height [mm]
θ	central region (pure shear) angle [^{o}]
F_y	Force of the uniaxial test [N]
d_y	Displacement after bias extension test [mm]

1 Introduction and Objectives

Non-crimp fabrics in composites are widely in use for a wide range of technical applications as automotive, aerospace and building constructions. For these branches, fibers and textiles are used for three reasons: their mechanical properties, such as tenacity, elongation, etc., their unique high ratio of surface to mass and their variable porosity. Thus manufacturing of non-crimp fabrics is an important step in the whole process fulfilling the homogeneous properties.

The aim of the thesis is the investigation and analysis of the mechanical and geometrical properties of multiaxial non-crimp fabrics. Non-crimp fabrics are produced with different parameters, such as pattern type, stitch length and warp yarn tension and to examine their characteristics by two different methods.

The plan of work is based on the selection of machine and material parameters within the test planning. Subsequently in chapter 3 the preliminary preparation of samples is described followed by the programming and main experiments according to the test plan. On the one hand, microscopy is used to observe the deformation of the fabrics influenced by the stitch length and pattern type.

On the other hand, with a bias extension test the relation between different parameters will be analyzed with the help of Apodius systems. The evaluation and data interpretation is performed with the application Excel and a Matlab tool.

The production of fabrics will be carried out with a warp knitting machine with multiaxial weft insertion, Copcentra MAX 3 CNC of LIBA Maschinenfabrik GmbH, Naila. This warp knitting machine is equipment of the Institut für Textiltechnik (ITA) of RWTH Aachen University and provided for the project.

The analysis of the deformation of the samples will be investigated with a light microscopy in particular with Microscope Leica DM 4000M. The bias extension test will be carried out with ZWICK Z100 testing machine of Zwick GmbH & Co. KG, Ulm.

2 State of the art

This chapter comprises a short introduction to non-crimp fabric (NCF), an overview of structure of different kind of textilies and production technologies.

Non-crimp fabrics (NCF) are warp-knitted products manufactured on warp knitting machines with multiaxial weft insertion. The manufacturing is essential for the development of the mechanical properties such as shear strain, tensile strength, etc. Hence, in the following chapters, the production process and the crucial machine parameters are emphasized.

2.1 Textiles

Textile structures are available in a large range of different types. In Figure 2.1 one classification of textiles structures and their subgroups is shown.

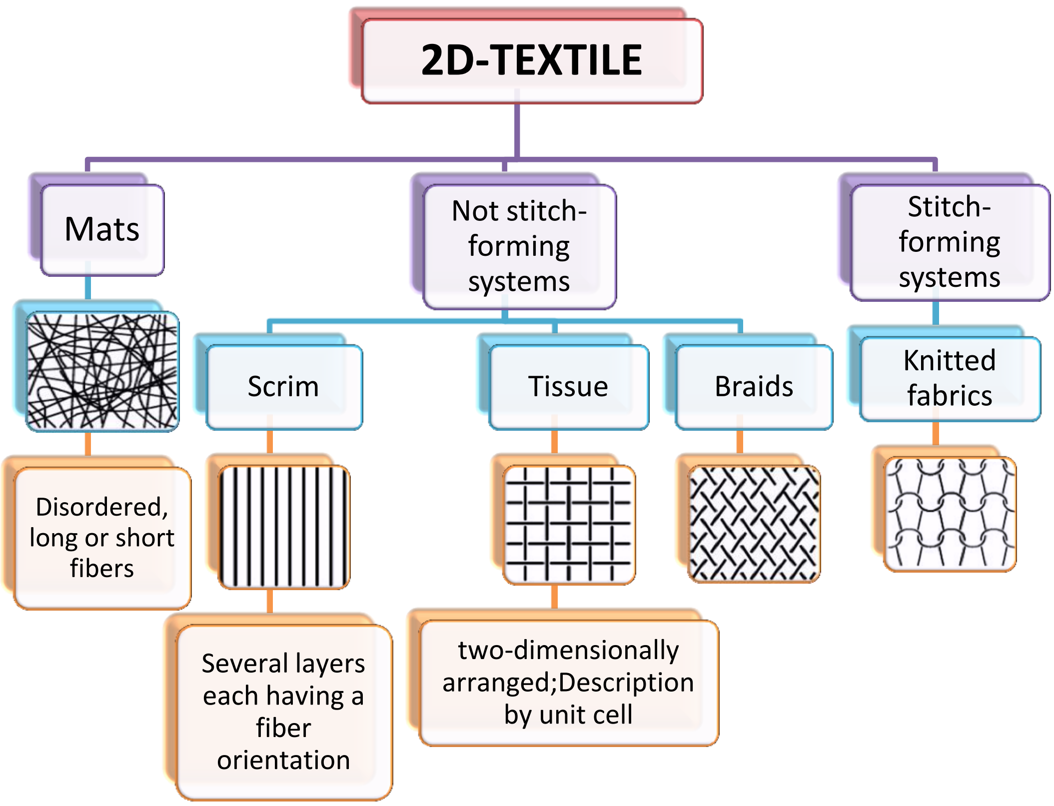


Figure 2.1: Classification of textiles structures [Lom11]

Textile structures can be divided into two- and three-dimensional structures. Most woven fabrics and knits as well as noncrimp fabrics, braids, and nonwovens belong to the first group.

Apart from conventional textile structures that are predominantly used in clothing and hygiene products, there is a large variety of considerably more complex textile structures used in technical applications, as shown in Fig. 2.2.

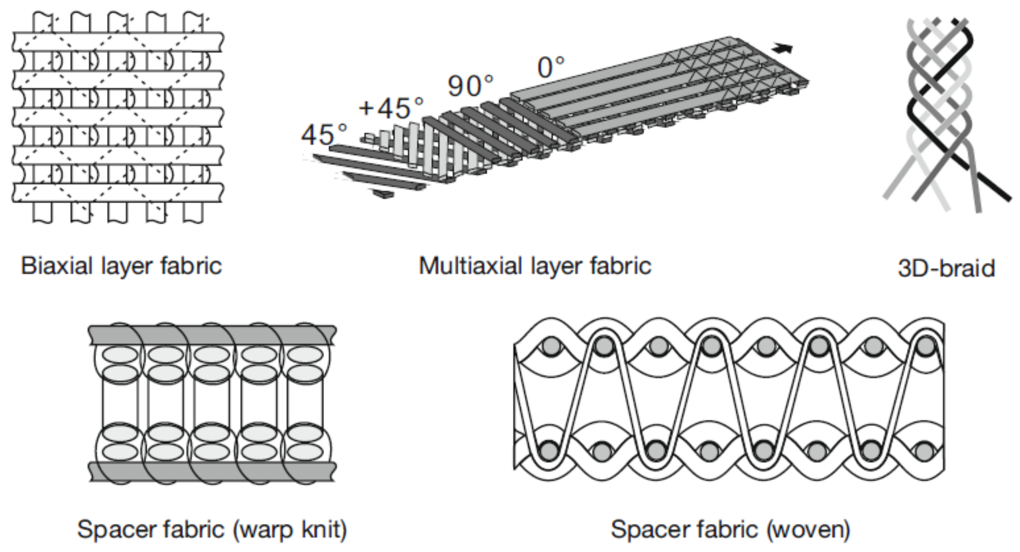


Figure 2.2: Complex textile structures for technical applications [GVW15]

In Fig. 2.2 an overview of different NCF structures, braids and woven structures is given. Non-crimp fabrics are defined as drawn parallel oriented layers of reinforcing threads or tows, which are positioned by means of an additional fixation material. These fabrics are warp knitted products manufactured on warp knitting machines with mutliaxial weft insertion and have been developed for allowing spherical deformation (drapability).

The most successful manufacturer of warp knitting machine is LIBA Maschinenfabrik GmbH, Naila and KARL MAYER Malimo Textilmaschinenfabrik GmbH, Chemnitz.

The reinforcing yarns can be bound in different ways. In one, the stitch length and distance between the reinforcing yarns coincide (coursewise), and then the yarns are connected in their original position. This technology is mainly used in biaxial fabrics. In the other way, the stitch length is constant and does not coincide with the distance between the reinforcing yarns (non-coursewise). Then, the yarns can be damaged and also shift from their original position. This method is often used in the production of multilayer, non-crimp fabrics.

Normally, the stresses of fiber-reinforced composite components are not mono- or biaxial. Therefore, for the use of biaxial textiles it is necessary to lay several layers in different orientations above one another to reinforce a component with regard to multiaxial loading. This procedure generates a large quantity of waste by cutting the layers in different orientations. It also increases the amount of time for the production of a composite component. Warp-knitted, multiaxial multi-ply fabrics were developed to eliminate the aforementioned disadvantages.

2.2 Warp-knitted non-crimp fabric (NCF)

In this chapter, the main characteristic of biaxial and multiaxial are explained. The focus is a hereinafter only multiaxial with weft insertion and they will be dealt as the main research focus.

2.2.1 Structure

Knitting processes with loop formation in production direction are called warp-knitted fabrics.The compound needles are assembled on a continuous needle bar and moved together during the loop formation. In warp-knitted NCFs the loop formation is used to bind reinforcing layers together. These processes are very flexible in respect to layer setup and fibre orientation, but they are limited to a constant width and area weight.

There is coursewise and non-coursewise fixation of the reinforcing threads existing. In machine with coursewise weft insertion, every warp and weft thread is bound with a single knitting loop. The stitch length can be defined in the machine settings. The technology for coursewise biaxial and multiaxial NCF is called warp-knitting. In machines with non-coursewise weft insertion, the stitch length is independent to the position of the threads.

There exist non-coursewise biaxial and multiaxial NCF.Non-coursewise multiaxial NCFs are called warp-knitted multiaxial layers or stich-bonded fabrics.

Table 2.1: Characteristics of coursewise and non-coursewise non-crimp fabric [Lom11]

Characteristic	Coursewise weft insertion	Non-coursewise weft insertion
Fiber damage	-	+
Dislocation of the reinforcing threads	-	+
Variability of the stitch length	+	+
Complexity of the machine technology	+	-
+Higher/ -Lower		

Biaxial warp-knitted NCF

Biaxial warp-knitted are made out of at least three thread systems:

- Pillar threads (0º),
- Weft threads (90º) and
- Warp-knitting yarns.

The reinforcing threads are fed parallel (pillar threads) and perpendicular- respectively diagonal- (weft threads) to the process direction. The distance between those threads is variable. The warp-knit yarns normally consist of thermoplastic materials such as PE or PA, normally PES. Figure 2.3 shows a scheme of biaxial warp-knitted fabrics with coursewise and non-coursewise weft insertion and different yarn spacings is shown.

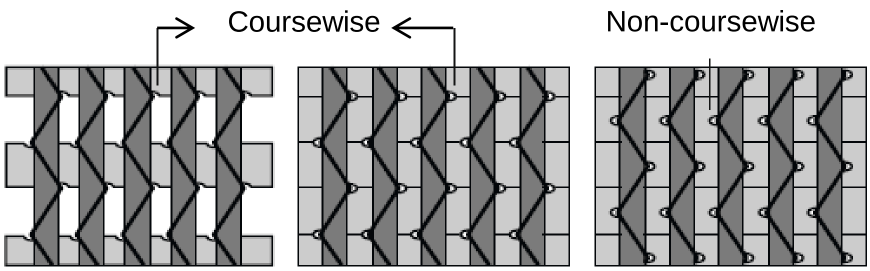


Figure 2.3: Biaxial warp-knitted non-crimp fabrics with coursewise and non-coursewise weft insertion [Lom11]

Multiaxial warp-knitted NCF

Multiaxial warp-knitted NCF with coursewise weft insertion is made of up four reinforcing fibre layers consisting of diagonal weft threads (e.g. 45º), weft threads (90º) and warp threads (0º). They are fixed by using warp-knitting yarns [Anon,1989]. [Lom11]

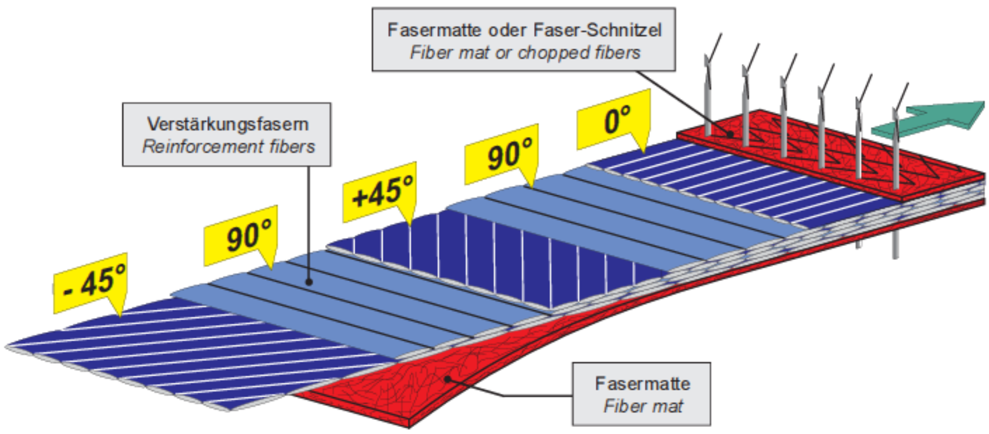


Figure 2.4: Schematic set-up of a multixial warp-knitted non-crimp fabric. [Lib10]

Multiaxial warp-knitted NCF with non-coursewise weft insertion consist of a current maximum of seven parallel layers of rovings or spread fibre tows.

The orientation of the single layers can be freely adjusted to between -20º and +20º relative to the production direction. On the top side of the fabric, an additional layer of 0º can be appliyed. All single fibre layers are fixed together with a warp yarn.

Parallel reinforcement fibre plies are placed on top of each other in different multiaxial orientations as required in the structure part. Nonwovens, fibre mats and/or other materials can be added on the outer surfaces or inbetween the single plies. The whole reinforcement complex is fixed by a loop system.

2.2.2 Production of NCF

In coursewise weft insertion machines (Fig. 2.5), the knitting unit, a beam with multiple pillar threads (0°), a transport system for weft insertion (90°), and a take-up unit are mounted on a large turntable, which rotates around its own vertical axis.

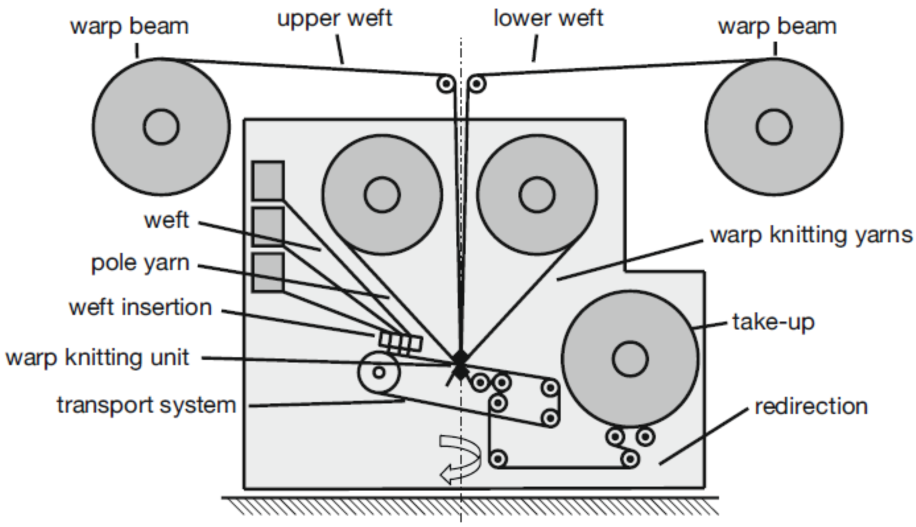


Figure 2.5: Coursewise multiaxial warp-knitting machine [GVW15]

The working principle of production weft insertion machine is similar to biaxial warp-knitting machine. The standard machine configuration consists of three weft carriage systems, which are adjustable in small ranges or infinitely between –45° and +45°. The single-fiber layers are filled in consecutive steps into the weft lay-in units of the transport system. [GVW15]

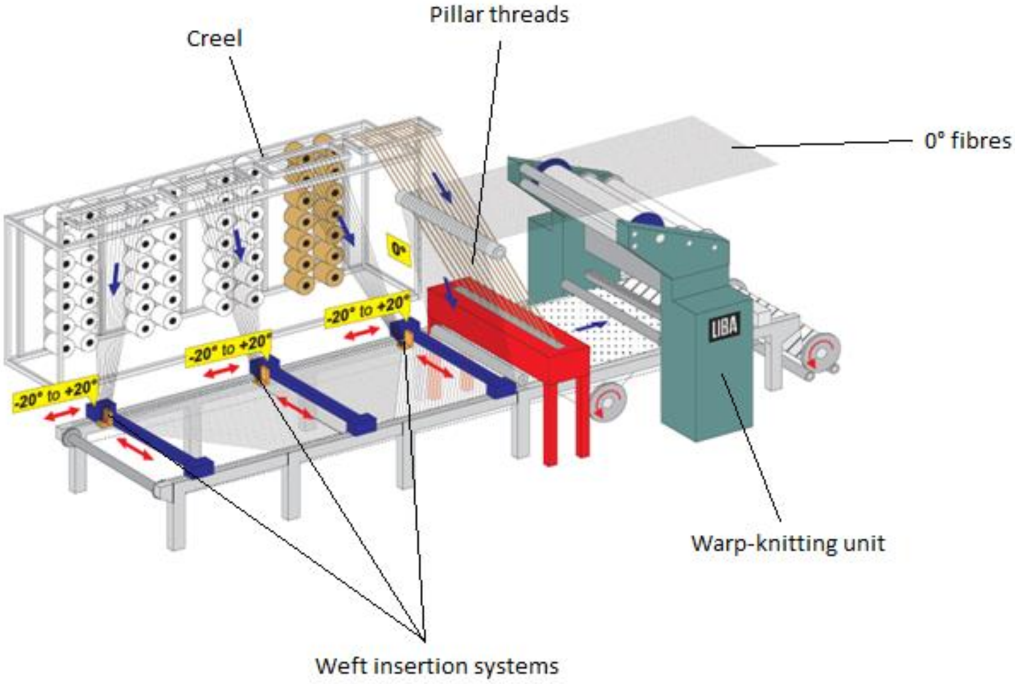


Figure 2.6: Machines for the production of NCF with coursewise weft insertion [Lib10]

The **weft carriage systems** are mounted on a portal, which is positioned above the transport systems of a warp-knitting machine with weft insertion. The weft carriage systems swings permanently between the two transport systems. Thus the weft carriage system take-off takes threads out of a stationary creel and supplies these threads to the transport systems.

In multiaxial weft insertion maschine exist two substantial weft insertion technologies:

- Insertion of endless weft threads and
- Insertion of finite weft threads.

The insertion of finite weft threads was developed for the precise and distorsion-free placing of discontinuously and continuously spread fibre tows made of carbon.

In the **warp-knitting module**, the loose fibre layers are fixed together with knitting loops. In Figure 2.7 shows the different knitting elements is shown. The motions of the knitting elements are generated with eccentric gears and corresponding actuating levers. Each knitting element has its own gear. The eccentric gears are driven by three phase asynchronous motor with servo converter, which is controlled electronically [Lom11]

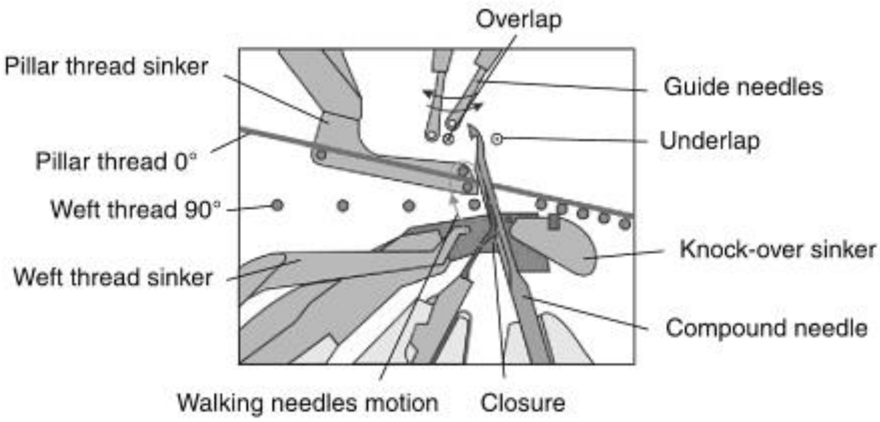


Figure 2.7: Knitting elements and walking needle concept [Lib10]

Warp-knitting machines with biaxial weft insertion are produced mainly with working widths from 102 to 245 inches and gauges from 3.5 to 24.(a guage is a defined as the number of needles per inch (25.4mm)).

In multiaxial weft insertion machines the warp- knitting module is nearly identical in construction and equipment with the biaxial module.There are warp-knitting machines with gauges from 3.5 to 14 needles per inch and working widths between 50 and 152 inches.

The **take-up module** is located towards the warp- knitting module and consists of a weft thread cutting device, a suction device, a fabric take-off and a fabric wind-up. The cutting device detaches the weft threads ends from the transport chain after the warp-knitting elements. For the fabric take-off, mechanically or electronically controlled systems with two or three rollers are used, which provide an appropiate tension in the fabric.

There exist different stitch types respectively knitting patterns to join the loose fiber layers together. The stitch types are predetermined by the scaling of the underlap of the guide bar. The most common stitch types are pillar, tricot, and plain (Fig. 2.8). The stitch type and the stitch length affect the drapeability of the fabric. [Lom11]

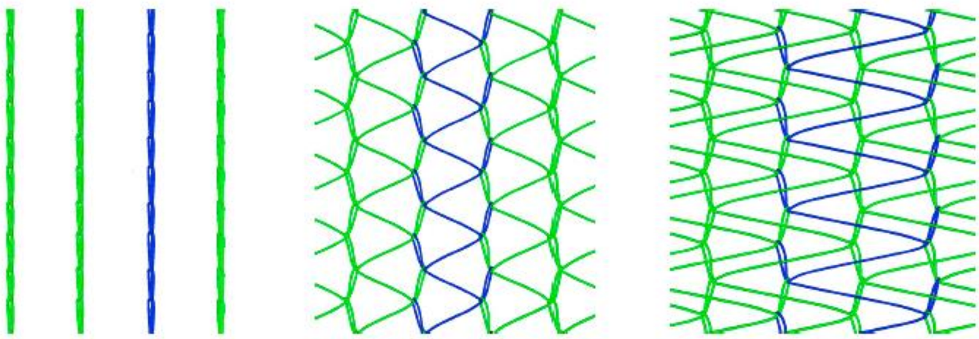


Figure 2.8: Stitch types- pillar (left), tricot (middle) and plain (right)[Lom11]

For this work, the tricot machine with multiaxial weft insertion will be used and specifically the Copcentra MAX3 CNC machine by LIBA GmbH, Naila, Germany.

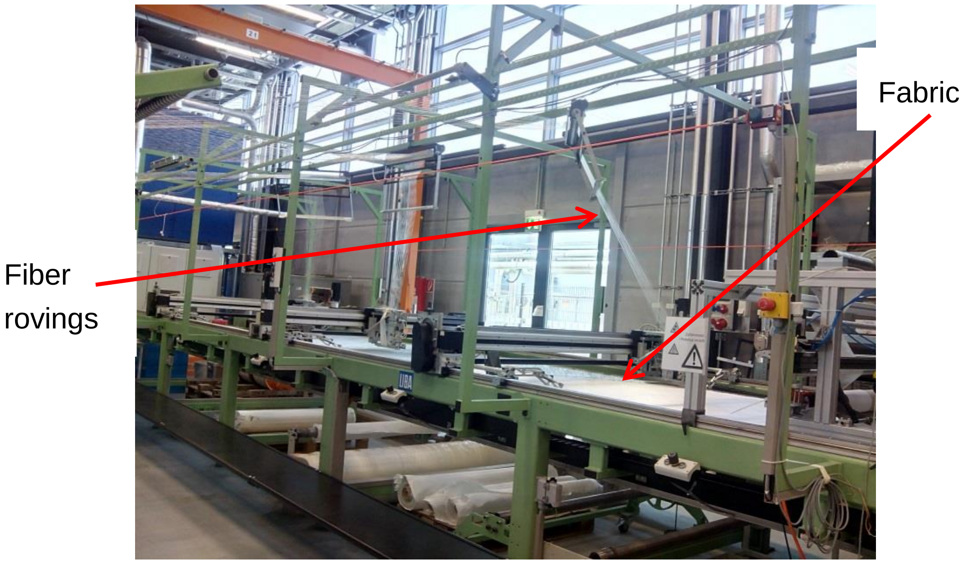


Figure 2.9: Copcentra MAX 3 CNC with additional fiber chopper device [ITA]

LIBA walking needle concept

In addition to the standard vertical knitting motion, the compound needle is also operated in horizontal direction - in direction of the fabric feed. This ‘walking’ needle motion assures an improved stitching process for all light and heavy weight stitch bonded structures.

Guide needles inserts the warp yarn into the knitting compound neddle. The compound needles puncture the supplied loose roving layers or fibre mats in every stitching course. Accordingly, the warp yarn are laid around the compound needles. The sinking of the needle with capture yarn through the layers completes the stitch. The co-operation of the needles, guides closure and sinker bar enables the stitch formation. Additional the implementation of pillar threads via a bar for 0º-reinforcement is feasible. Finally, the stitches fix the loose roving layers together. These layers build the non-crimp fabrics and are taken up.

The puncture of the fabris through the compound needles and the simultaneous movement of the fabris can lead to damage and deflection of the reinforcing threads.

In walking needle system, an additional horizontal movement- in the direction of production-during the influence of the needles. The degree of horizontal needle movement can be adjusted manually with an adapted actuating lever.

- Minimum load and tension = reduced wear on the needle system
- Reduced stitch holes = improved fabric quality
- Reduced friction = high production speed

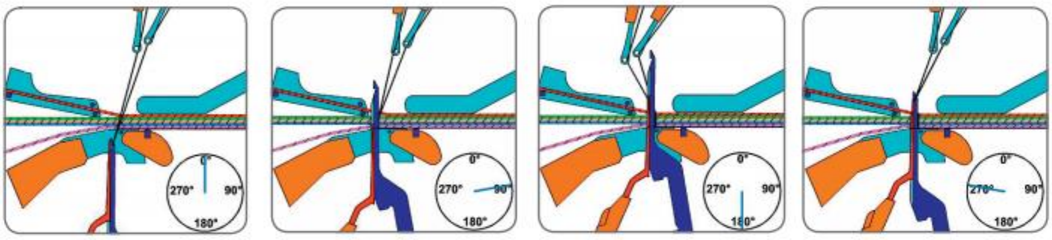


Figure 2.10: LIBA walking needle concept [Lib10]

Central Computer System

With the central computer system, the main parameter of the production can be fixed and change:

- Saving and calculation of all product information,
- Free programming of layer angles of all layer systems from - 20° to + 20°,
- Style change with different layer angles without mechanical changes,
- Customer-, product- and Error data base,
- Internal log of operational data,
- Ready for linking to several machines or to control position,
- Service support system for fast customer support and
- Sealed switchboard for safe processing of carbon.

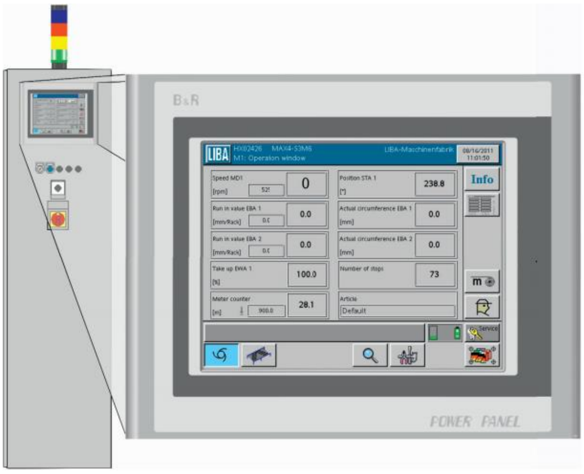


Figure 2.11: LIBA Central Computer System [Lib10]

2.3 Machine setting and operating material

The following explained machine set-ups and different parameters, which have to take cognizance before the production.

Currently the operator enters among others the most important process parameters into the WKM CNC panel:

- Pattern type,
- Stitch length,
- Warp- let-off value and
- Machine speed

These parameters above are fed independent of each other. The CNC adjusts automatically the yarn delivery speed according to the machine speed without changing the warp let-off value.

3 Materials and Methods

The methods can be divided into two parts. The first part includes all preliminary methods, which are necessary to prepare the trials before the tests. The second part consist of the main test methods.

In this chapter, all steps are explained in details and the aspects to bear in mind before analysing. Also the used material is described.

3.1 Materials

For the production and testing, the following materials are used:

Glas: By mixing stone products (sand, kaolin, limestone, colmanite) at 1,250°C liquid glass is produced. This liquid is pumped through microfine nozzles and simultaneously cooled in order to produce glass fibre filaments. Multiaxial interlaid complexes (NCFs) of variable orientation and individual layer arrangement always exhibit the best mechanical characteristic values and this bidirectional complexes are available in orientations of 0°/90°.[www15]

HYBON 2001 roving from PPG Fiber Glass is a continuous filament, single-end strand roving designed to reinforce polyester, vinyl ester and epoxy resin systems. [PPG15]

Some of technical characteristics:

- Single-end roving that catenary-free and abrasion resistant.
- Rapid, complete and consistent wet out.
- Excellent unwinding performance and transfer from package to package.

The samples produced are made of 1200 Tex PPG Hybon 2001 glass fibers.

The stitiching yarn is made of 167 dtex Polyester (PES) yarn.

3.2 Preparation of samples

Different steps are necessary before performing the tests on the samples. Then all the different trial are done, they have to be cut with the standardized measure and prepared to be analyzed. In Fig 3.1 the process chain of the preparation of samples is illustrated.

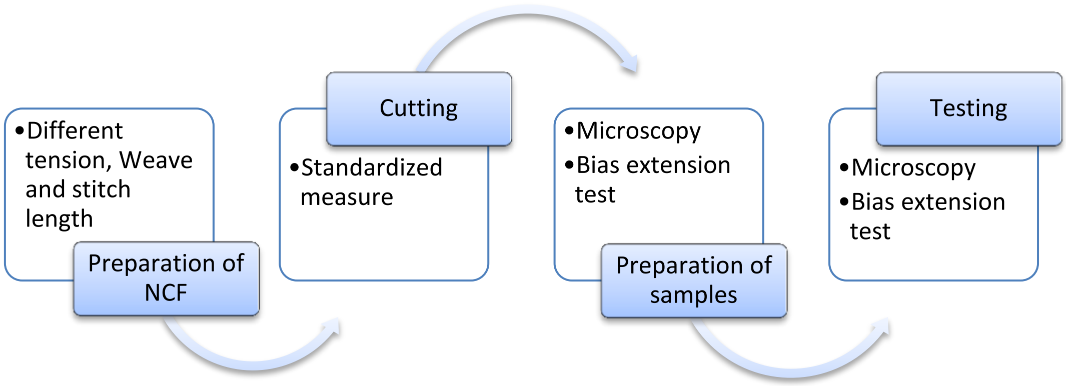


Figure 3.1: The process step by step

3.2.1 Preparation of NCF

In general usage, design of experiments (DOE) or experimental design is the design of any information-gathering exercises where variation is present, whether under the full control of the experimenter or not. This technique is a systematic, rigorous approach to engineering problem-solving that applies principles and techniques at the data collection stage so as to ensure the generation of valid, defensible, and supportable engineering conclusions. In addition, all of this is carried out under the constraint of a minimal expenditure of engineering runs, time, and money.

Consider the following diagram (Figure 3.2). There are three aspects of the process that are analyzed by a designed experiment.

- Those variables which influence the process directly are called factors
- Noise factors are those variables which cannot be adjusted but still have influence on the process
- The responses are those variables which are used for measuring process results.

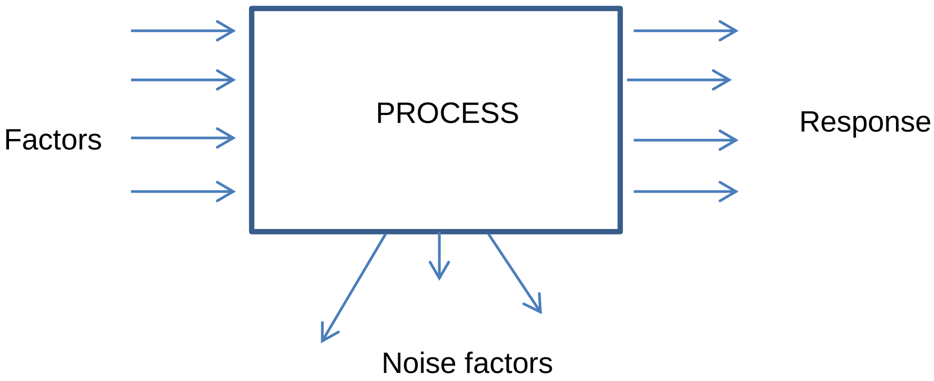


Figure 3.2: Sketch of methodology of design of experiments

There are 3 different pattern types, which will be analyzed: Tricot, plain and pillar. Different types of patterns are intended for different end uses since their design and mechanical properties vary significantly. The pattern type can be change with the WKM CNC panel by means of the respective code:

- Pillar: 1010,
- Tricot:1012 and
- Plain: 1023

On the other hand, the use of different stitch lengths affects the handling, drapability and properties of NCFs. Three different stitch lengths will be analyzed: 2 mm, 4 mm and 6 mm.

The current adjustment of the yarn tension is not actively controlled. The operator enters the warp let-off values according to the professional knowledge. The value adjustment depends on the current running position (material, pattern type, stitch length and layer thickness) and has to be modified by the operator if necessary.

To ensure production constant warp yarn tension among different positions set but also adjustable various stitch length depending on the requirements of finish product NCFs the interaction of the current control of the warp beams and a tension control is essential.

In all of the production process the speed of the machine is fixed on 25 m/h.

Taking all of the different parameters into account the following table is established.

Table 3.1: Overview of produced NCF

Weave	Stitch length	Layer	WEIGHT Pro layer	WEIGHT Total	EBC VALUE Min.	EBC VALUE Normal	EBC VALUE Max.
Pillar	2mm	45-45	300 g/m2 + 300 g/m2	600 g/m2	3300	3500	3700
		45-45	600 g/m2 + 600 g/m2	1200 g/m2	3600	3850	4100
		45-90-45	300 g/m2 +150 g/m2 + 300 g/m2	750 g/m2	3500	3700	3850
	4mm	45-45	300 g/m2 + 300 g/m2	600 g/m2	6100	6250	6400
		45-45	600 g/m2 + 600 g/m2	1200 g/m2	6300	6500	6700
		45-90-45	300 g/m2 +150 g/m2 + 300 g/m2	750 g/m2	6160	6320	6450
	6mm	45-45	300 g/m2 + 300 g/m2	600 g/m2	9000	9200	9450
		45-45	600 g/m2 + 600 g/m2	1200 g/m2	9250	9500	9850
		45-90-45	300 g/m2 +150 g/m2 + 300 g/m2	750 g/m2	9150	9350	9500
Tricot	2mm	45-45	300 g/m2 + 300 g/m2	600 g/m2	5300	5600	5850
		45-45	600 g/m2 + 600 g/m2	1200 g/m2	5400	5800	6100
		45-90-45	300 g/m2 +150 g/m2 + 300 g/m2	750 g/m2	5450	5750	6000
	4mm	45-45	300 g/m2 + 300 g/m2	600 g/m2	6900	7200	7500
		45-45	600 g/m2 + 600 g/m2	1200 g/m2	7150	7500	7950
		45-90-45	300 g/m2 +150 g/m2 + 300 g/m2	750 g/m2	7150	7400	7650
	6mm	45-45	300 g/m2 + 300 g/m2	600 g/m2	9500	9800	10050
		45-45	600 g/m2 + 600 g/m2	1200 g/m2	9850	10100	10500
		45-90-45	300 g/m2 +150 g/m2 + 300 g/m2	750 g/m2	9600	9900	10200
Plain	2mm	45-45	300 g/m2 + 300 g/m2	600 g/m2	7100	7400	7700
		45-45	600 g/m2 + 600 g/m2	1200 g/m2	7300	7800	8200
		45-90-45	300 g/m2 +150 g/m2 + 300 g/m2	750 g/m2	7200	7600	7900
	4mm	45-45	300 g/m2 + 300 g/m2	600 g/m2	8500	8800	9000
		45-45	600 g/m2 + 600 g/m2	1200 g/m2	8800	9100	9600
		45-90-45	300 g/m2 +150 g/m2 + 300 g/m2	750 g/m2	8700	9050	9350
	6mm	45-45	300 g/m2 + 300 g/m2	600 g/m2	10900	11300	11600
		45-45	600 g/m2 + 600 g/m2	1200 g/m2	11200	11500	12000
		45-90-45	300 g/m2 +150 g/m2 + 300 g/m2	750 g/m2	11000	11250	11500

The properties of the fabric are influenced by the selection of material, stitch length and warp knitting yarn.

Pillar, Tricot and Plain are analyzed because they are the most important rovings in the industry. For the same reason, two-Layers [+45^o,-45^o] are included in the study.

In the other hand, the motivation to select three layers is the possibility of analyzed other kind of sample significantly different to the others.

Minimum and maximum tension are been chosen cause are the limits for the machine and they represented the extreme situations and normal tensile is a value in the middle.

The weight pro layer is imposed by the characteristics of the machine. To two layers, two different weights are possible, 300 g/layer and 600 g/layer because they are the most common in the industry. For the trial with 3 layers, the maximum weight possible is selected. With a weight higher can be produced damages in the trials.

3.2.2 Cutting

For cutting the fabrics the cutting machine Cuttertisch Turbocut s 2501 CV is used. The machine is from the company Assyst-Bullmer GmbH, Mehrstetten, Germany [Ass] and it is capable of cutting from single ply up to lays of 25 mm. (see Fig.3.3)

Figure 3.3: Machine Turbocut s2501 CV at ITA

To operate the cutting machine, a CAD model is necessary. The fabrics are placed into the table of the machine and covered. The trials are vacuum packed for a better cutting. In the following figures the necessary measurements are illustrated.

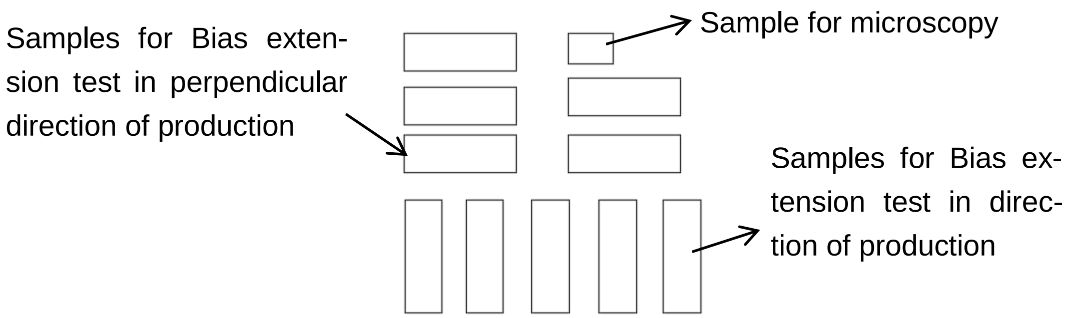


Figure 3.4: Design with AutoCad with standardized measures

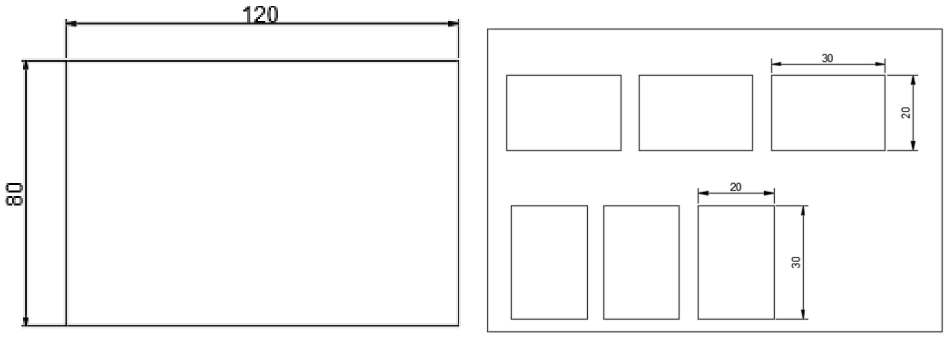


Figure 3.5: Samples for microscopy 120x80 mm (left) and specimens for microscopy (right)

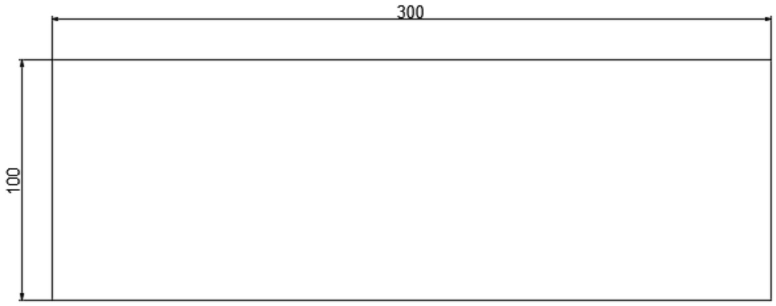


Figure 3.6: Samples for uniaxial extension test 300x100 mm

For the trials, which later will be tested with uniaxial bias extension test, have been produced 5 specimens with not the same direction of the stitch (see Figure 3.4)

Due to some problems with the cutting machine, the sample plain 2, layer [+45°/-45°], weight total 600 g/m^2, tension normal 7800 could not be used for further testing.

3.2.3 Preparation of the samples for microscopy

In this thesis two different tests are performed. One of them for the microscope and the other one for the uniaxial extension test. The specimens must be prepared and this is made in some steps. First the impregnation the trials in order to make easier the cutting. Then the cutting with the right measurement for the embedding and finally the infiltration the specimens with resin.

<u>Resign impregnation</u>

Before investigating the sampled by microscopy, they must be impregnated with a special resin.

Vacuum Assisted Resin Transfer Molding (VARTM) is a variation of Resin Transfer Molding (RTM) with its distinguishing characteristic being the replacement of the top portion of a mold tool with a vacuum bag and the use of a vacuum to assist in resin flow. After the impregnation occurs the composite part is allowed to cure at room temperature with an optional post cure sometimes carried out.

However RTM tends to be very expensive, and suffers from limited pre-preg shelf lives and short lay-up times. In addition, the process is highly labor intensive and quality control is difficult since the quality of the final product is highly dependent on the operator skills. With VARTM many of these limitations are eliminated because this process generally reduces lay-up times and makes the fabrication process more reproducible and consistent and less dependent upon operator skills.

The following steps have been realized:

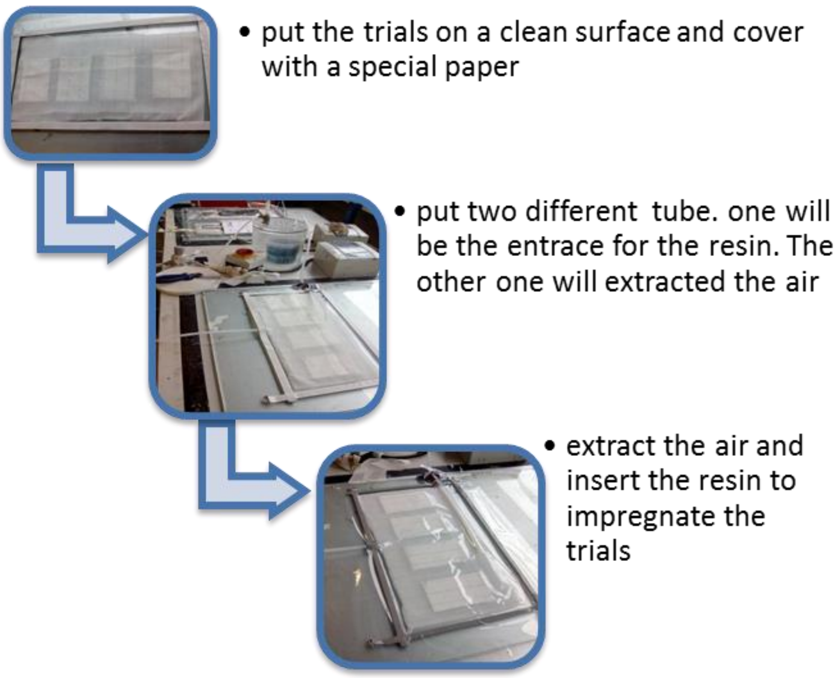


Figure 3.7: Steps for impregnation the trials for microscopy

Within the VARTM process, polymer composite parts are made by placing dry fiber reinforcing fabrics into a single part, open mold enclosing the mold into a vacuum bag and drawing a vacuum in order to ensure a complete preform infiltration with resin. In the last stage of the process, the mold is heated until the part is fully cured since VARTM does not require high heat or pressure. Resin infiltration is frequently facilitated using vacuum. [Moh04]

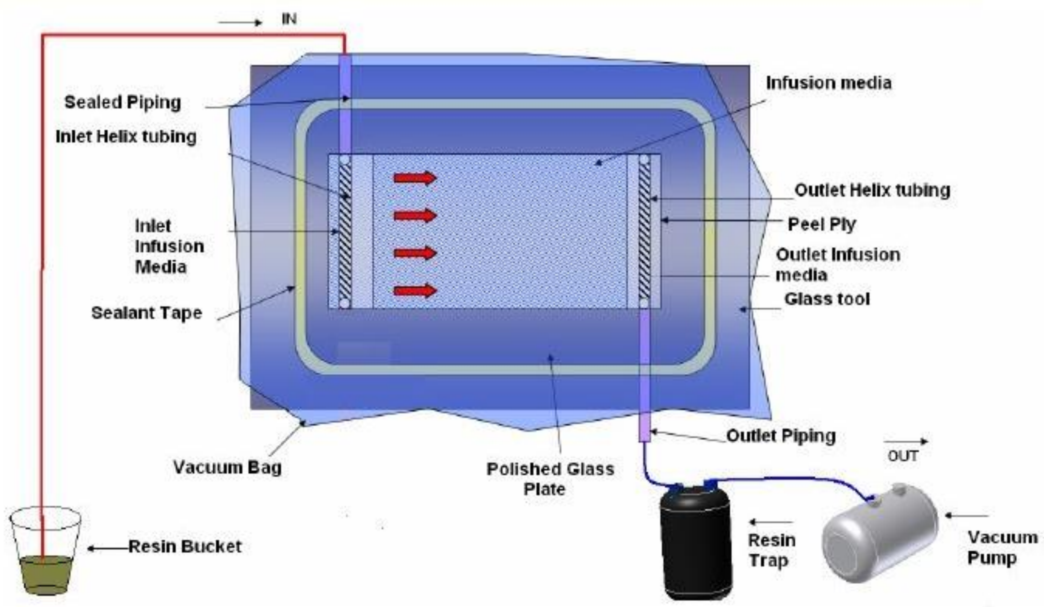


Figure 3.8: Top view of VARTM [Anu09]

<u>Cutting</u>

Having made the impregnation, the samples are cut with a multi-function tool.

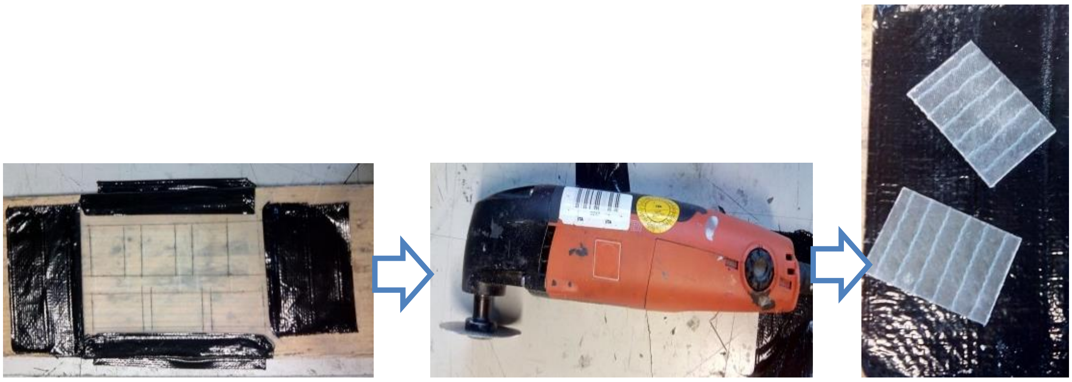


Figure 3.9: Steps for cutting the specimens

First the specimens are drawn in the samples and then are fixing with adhesive tape. When all are fixed, the specimens are cut with the precise measurement.

The finally specimen must be 30x20 mm in order to fit in the blocks for embedding and they are cut in two different directions. One in the direction A and the other one in the perpendicular direction B (see Fig.3.10).

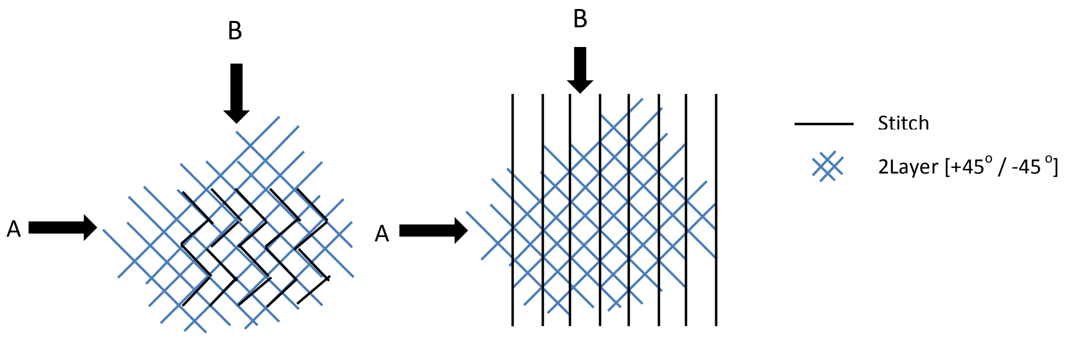


Figure 3.10: View of the direction of the specimens. Plain (left) and Pillar (right)

Embedding

Materials to be viewed in a light microscope generally require processing to produce a suitable sample. The technique required varies depending on the specimen, the analysis required and the type of microscope. In this case, the embedding is used. This technique is based in the infiltration of the fabric with a resin such as araldite, which can then be polymerized into a hardened lock for subsequent sectioning.

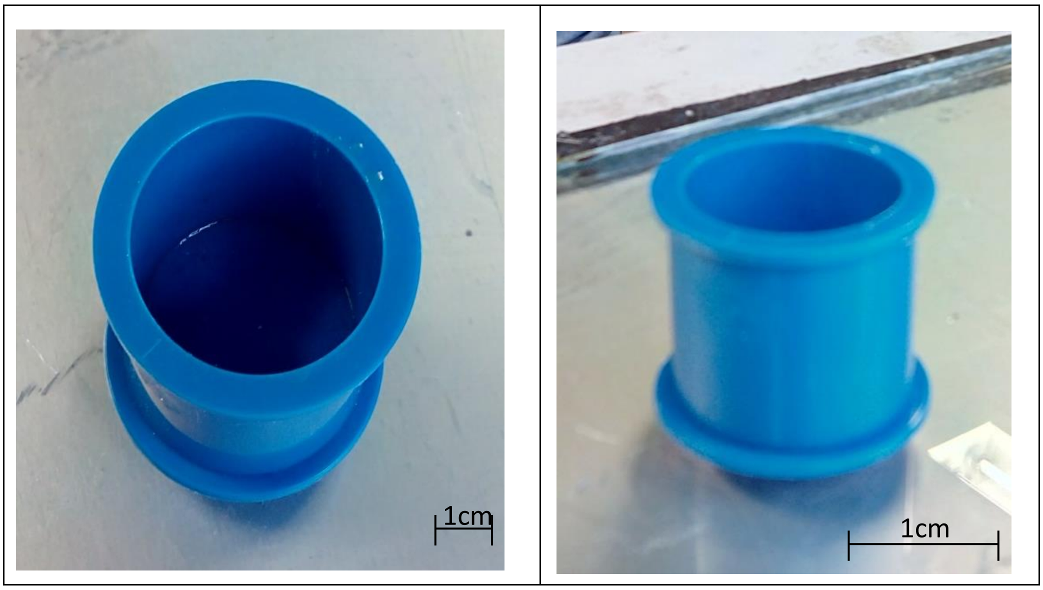


Figure 3.11: Blocks for embedding [ITA]

After the samples have been dehydrated, cleared, and infiltrated with the embedding material, they are ready for external embedding. During this process the samples are placed into molds along with liquid embedding material (resin) which is then hardened.

After this, the block must be grinding and polishing in other to obtain a better surface to analyze the specimens. The hardened blocks containing the specimens are then ready to be analyzed.

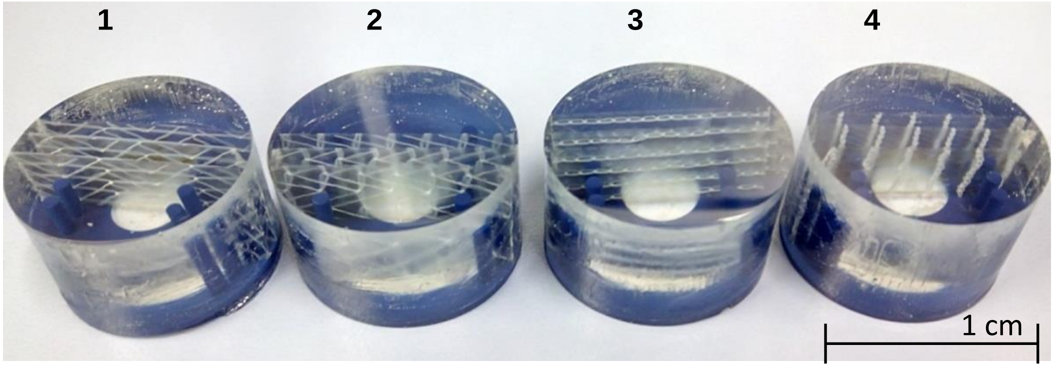


Figure 3.12: The embedded specimens

Once the embedding is finished, the blocks with the specimens for microscopy can be observed. There are 4 different specimens:

1. Plain 6mm [+45^{o}/-45 ^{o}] direction A
2. Plain 6mm [+45^{o}/-45 ^{o}] direction B
3. Pillar 2mm [+45^{o}/-45 ^{o}] direction A
4. Pillar 2mm [+45^{o}/-45 ^{o}] direction B

These 4 specimens are selected because of they define the boundary conditions and they describe the most important characteristic in the industry.

3.2.4 Preparation of samples for bias extension test

For the trials, which will be tested with the uniaxial test, some previous steps are necessary.

Figure 3.13: Steps for preparing trial before uniaxial test

First the pieces of carton must be cut with the correct measures, 100x50 mm in order to protect the samples and to get a relation for the sample of height/width equal a 2/1 that is 200X100 mm. This is necessary for the bias extension test but will be discussed in detail in the next chapter.

For this step, a special machine is used. This machine enables cutting of many pieces at the same time with the help of standardized mold, which are used to get the correct measures.

Secondly a special glue is used to stick the carton. Araldite 2011 is two component epoxy paste adhesive. Araldite A and Araldite B make up the glue. These two compenents must be mixture in a correct ratio (Mix ratio by weight: 100:80). The strength and durability of a bonded joint is dependent on proper treatment of the surfaces to be bonded.

At the very least, joint surfaces should be cleaned with a good degreasing agent such as acetone, iso-propanol (for plastics) or other proprietary degreasing agents in order to remove all traces of oil, grease and dirt.

When the glue is ready, the cartons are sticked over the samples. In the Fig 3.9 the final results is shown.

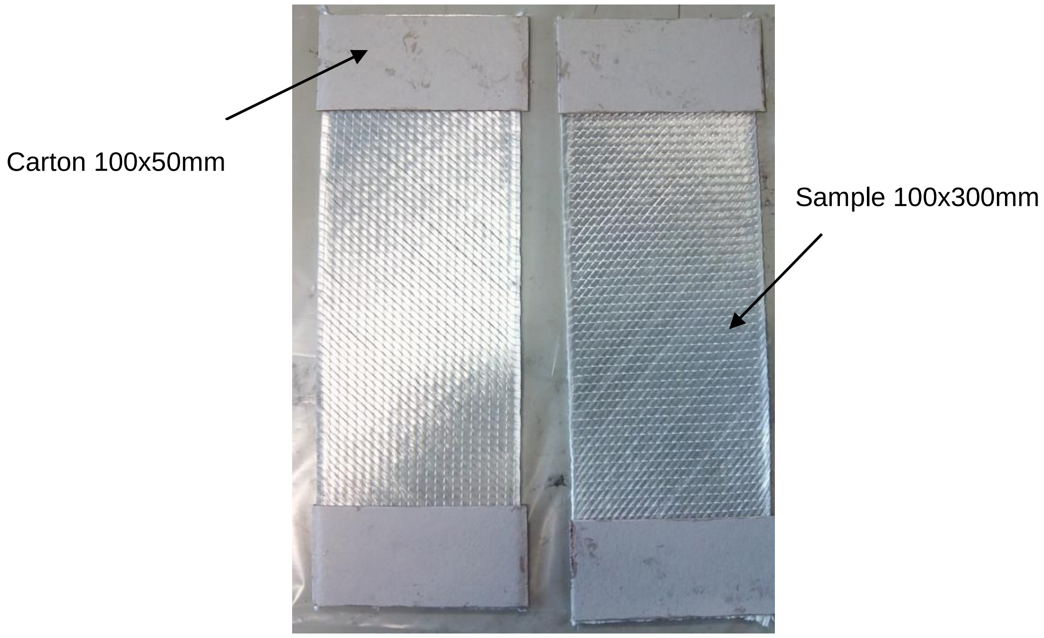


Figure 3.14: Steps for preparing trial before tensile test

3.3 Test methods

Once the specimens are ready, the testing can be started. In this chapter the theoretical aspect for tests and the overview of the machines is described in order to clear the key aspect.

3.3.1 Microscopy

Microscope Leica DM 4000M is used to analyze the samples. This is a light microscope, so called because it employs visible light to detected small object. In Figure 3.13 an image and different parts of the microscope is shown.

The most notable technical characteristics are that it can be used with all common incident light contrast methods.

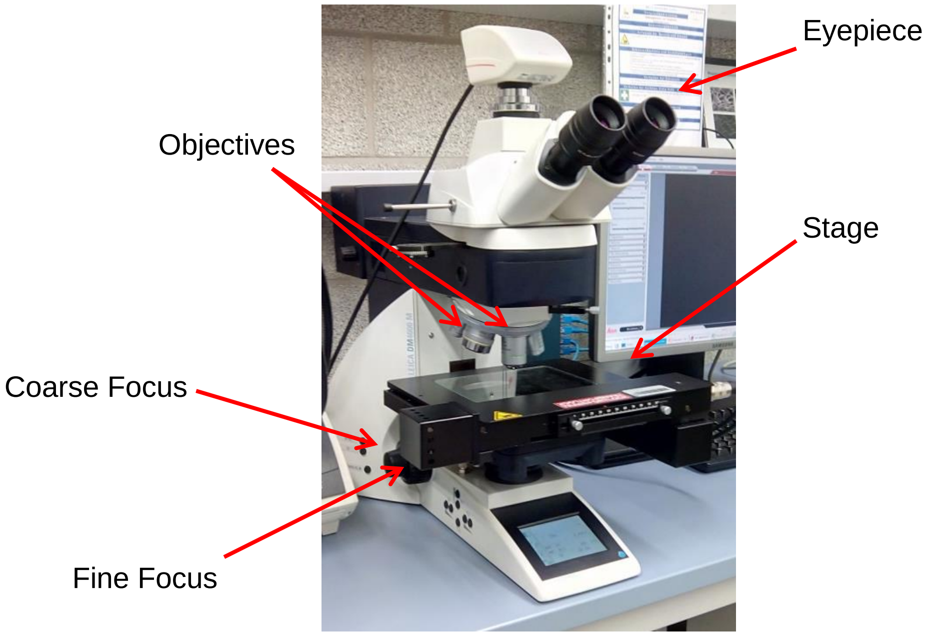


Figure 3.15: Microscope Leica DM 4000M [ITA]

With the different objectives from the microscope can be used for testing. Therefore three of them, the most common in the industry, are used: x10, x2.5 and x20. That means, for example, that an enlargement of samples of 10x10 is applied. This results because the itself microscope has an enlargement of 10.

To get a good picture quality, first the objective have to put in the right position with a remote control and then the focusing is realized with the coarse and fine focus. Furthermore, the software tools can be used. With these tools, the light, the contrast can be adjusted. The user interface is easy to use. Function keys, contrasting techniques and other microscope parameters are easily configured on the computer in accordance with the preferences or the needs of the working environment.

When all parameters are adjusted, the photo of the sample can be taken.

3.3.2 Bias extension test

The bias extension test is used to determine the nonlinear shear stiffness of woven composites in pure shear. The objective of this work was to gain a better understanding of the material properties of woven glass fabrics and how to best determine and predict their shear angle properties when subjected to tensile bias testing.

A sample of material, with the dimension of the test sample in the loading direction relatively greater than the width, and the yarns initially oriented at ± 45-degrees to the loading direction, is gripped at two ends (see Fig. 3.14). A tensile force is applied at the gripper. The force required to deform the material is recorded at the gripper as a function of gripper displacement.

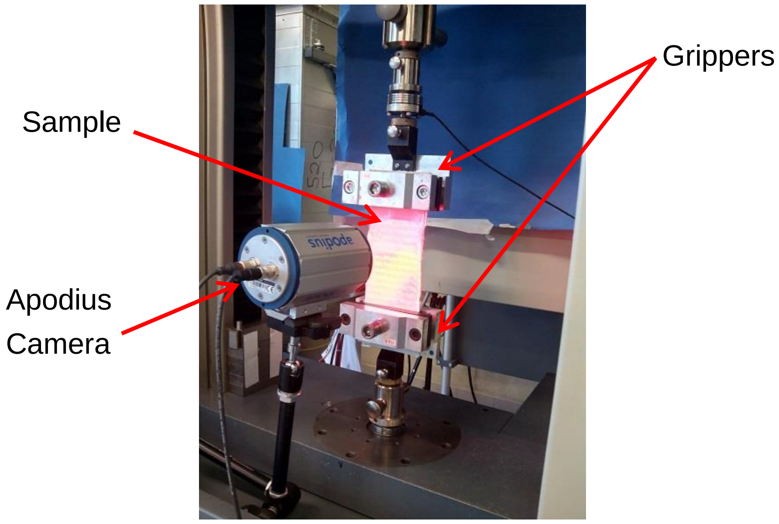
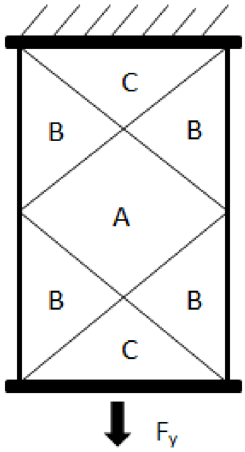


Figure 3.16: Bias extension set-up [ITA]

When the initial length of the sample (l_{BE}) is more than twice the width of the sample (w_{BE}), there exists a perfect pure shear zone in the center of a sample (zone A in figure 3.15). The shear angle in region A can be assumed to be twice that in region B, while region C remains undeformed assuming yarns being inextensible and no slip occurs in the sample.



Zone A: a perfect pure shear

Zone B: the shear angle in region B can be assumed to be half that in region A

Zone C: remains undeformed

Figure 3.17: Illustration of characteristics zones in a fabric specimen

Once the test is complete there are three main ways to determine the shear angle of the material during the test. The first method calculates the shear angle using the theoretical equation based on the kinematic analysis of the bias-extension test.

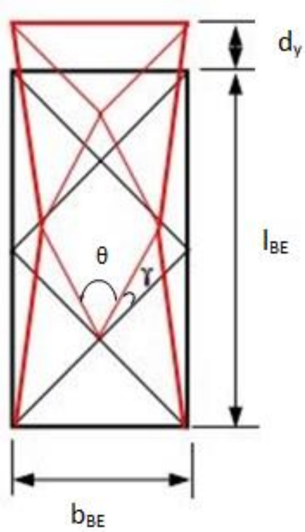


Figure 3.18: Deformation of bias sample [PC03]

A simple kinematic analysis of a bias extension sample in figure 3.16 gives us the shear angle in zone A, γ, as a function of fabric size and the end displacement as:[PC03]

$$\gamma = 90^o - \theta \tag{3.1}$$

$$\cos\theta = \cos\theta_0 + \frac{d_y}{2 \cdot (l_{BE} - b_{BE}) \cdot \cos\theta_0} \tag{3.2}$$

$$F_n(\gamma)=\frac{1}{(2\cdot l_{BE}\text{-}3\cdot b_{BE})\cos\gamma}\cdot\left(\left(\frac{l_{BE}}{b_{BE}}\text{-}1\right)\cdot F_y\cdot\left(\cos\frac{\gamma}{2}\text{-}\sin\frac{\gamma}{2}\right)\text{-}b_{BE}\cdot F_n\left(\frac{\gamma}{2}\right)\cdot\cos\frac{\gamma}{2}\right) \tag{3.3}$$

Local fiber orientation is extremely important to the ultimate strength and crash-worthiness of a specific component, particularly as molding capabilities grow and parts become more complex. Therefore the measurement of the fiber angle is analyzed by the Apodius vision system (AVS). The basis of the technology was development and is being marketed directly by a German company called Apodius, which is a spinoff from the plastics technical program at RWTH. [www15a]

It is a modular, production integrated inspection system for composite structures in general and the production of textile fabrics in particular. The measuring data is analyzed with a frequency of 10 Hz and a resolution of 0.1°.The detection of defects based on image processing and texture analysis.[Apo15]

The software allows taking photos of the samples in short intervals of time. A clear and intuitive interface enables to operate quick and purposeful. After ending the process a data file is created with the angle corresponding to each photo.

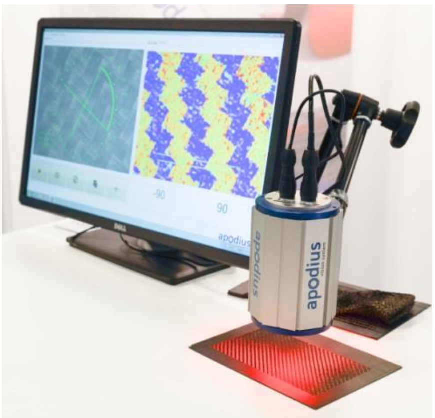


Figure 3.19: Fiber angle measurement with the Apodius Vision System [Apo15]

Once the photos are taken, the results must be analyzed. The force and the angle are measured and from these results other parameters can be calculated. For this work Matlab tool is used. From some functions, which already exist, standardized distance, force, shear angle and shear force, among some more can be obtained. The program creates an excel document and with these, plots and chart are obtained, which after are compared with other samples with different initial technical characteristics.

4 Results

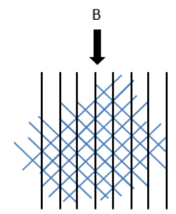
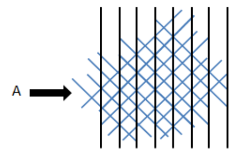
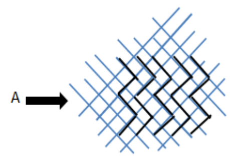
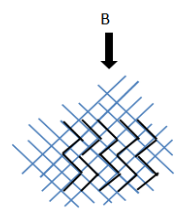
There are two parts in this chapter. One of these is to results from microscope and the other one of the mechanical tests. In the first part, the different photos from the samples are exposed and the possible defects and causes are mentioned.

The other part describes the results from the bias extension test. The theoretical calculations are compared with the experimental numbers in order to take conclusions.

4.1 Microscopy

As indicated above the specimens are been examined with three different objectives. In the following figures can be observed the differences between them.

Table 4.1: Overview of samples for microscopy

Sample	Characteristic	Image
Sample 1	Pillar 2mm [+45^{o}, 45^{o}] EBCmin=3300	
Sample 2	Pillar 2mm [+45^{o},-45^{o}] EBCmin=3300	
Sample 3	Plain 6mm [+45^{o},-45^{o}] EBCmin=10900	
Sample 4	Plain 6mm [+45^{o},-45^{o}] EBCmin=10900	

4.1.1 Sample 1

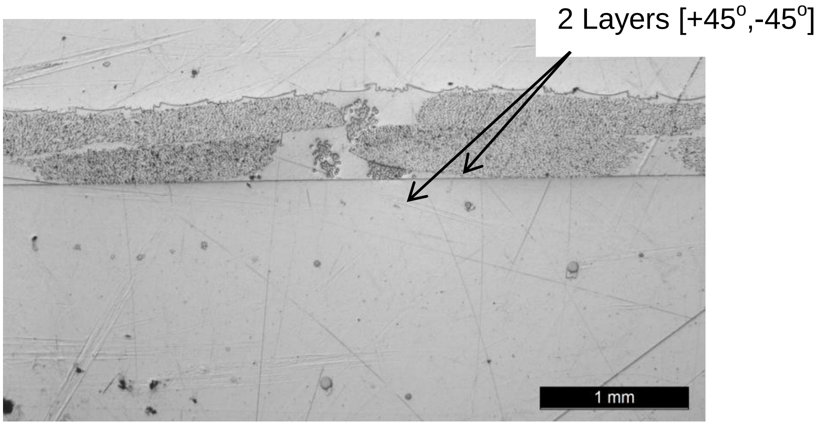


Figure 4.1: Pillar 2mm, direction B. Objective: x2.5

With the smaller objective, the two layers can be observed and the wave between them.

Known the scale, the width for the specimen can be calculated and compared with the other specimens.

The width is measured in the image and then with the scale it is transformed to the real measurement. For example in the Figure 4.1, the measured width is 20 mm and the scale indicates that 44 mm is equal a 1 mm in the reality therefore the real width for this specimens is 0.45mm.

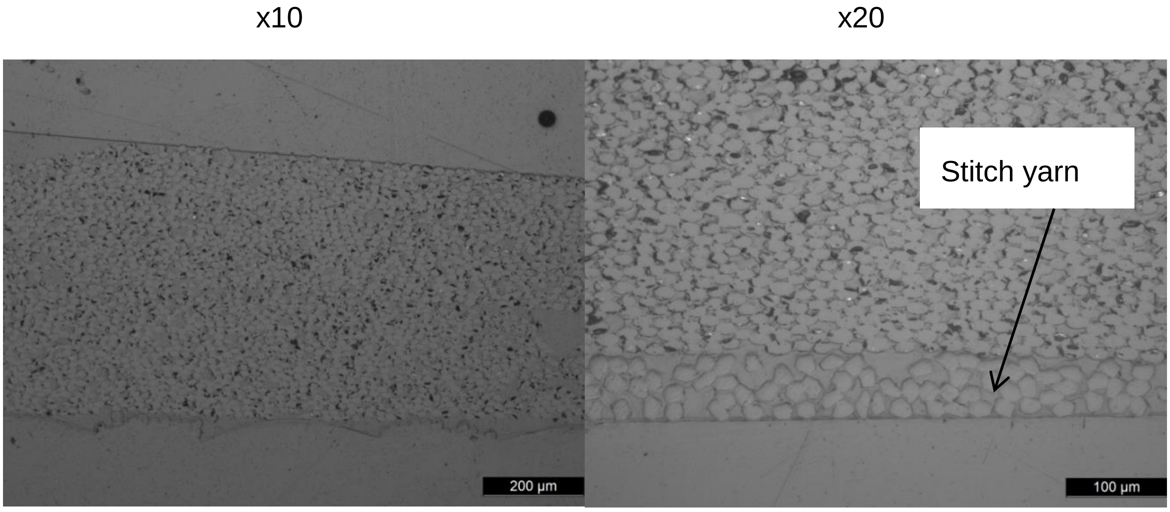


Figure 4.2: Pillar 2mm Objective: x10 (left). Pillar 2mm Objective: x20 (right)

With these objectives is more difficult to see the two layers but defects and the differences between the stitch and the fibers can be observed. For example in figure 4.2 two zones clearly different is shown. The up zone corresponds to fibers from the layer and the down zone belongs to stitch fibers.

4.1.2 Sample 2

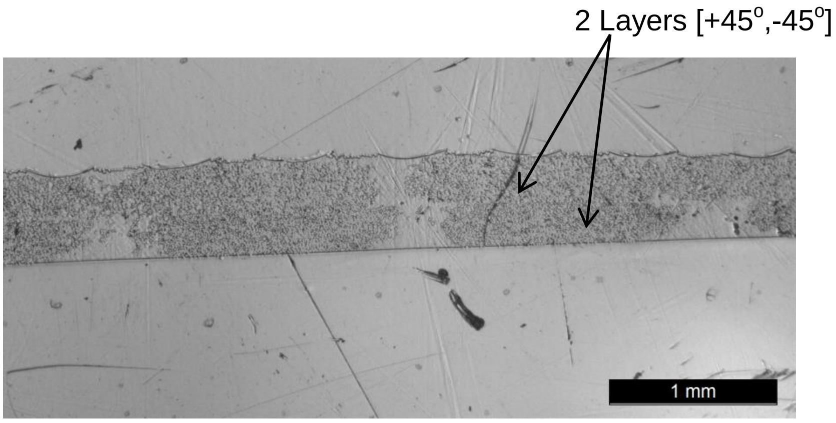


Figure 4.3: Pillar 2mm, direction A. Objective: x2.5

Like explained before, the real width is calculated. In this case the length is 0.57 mm.

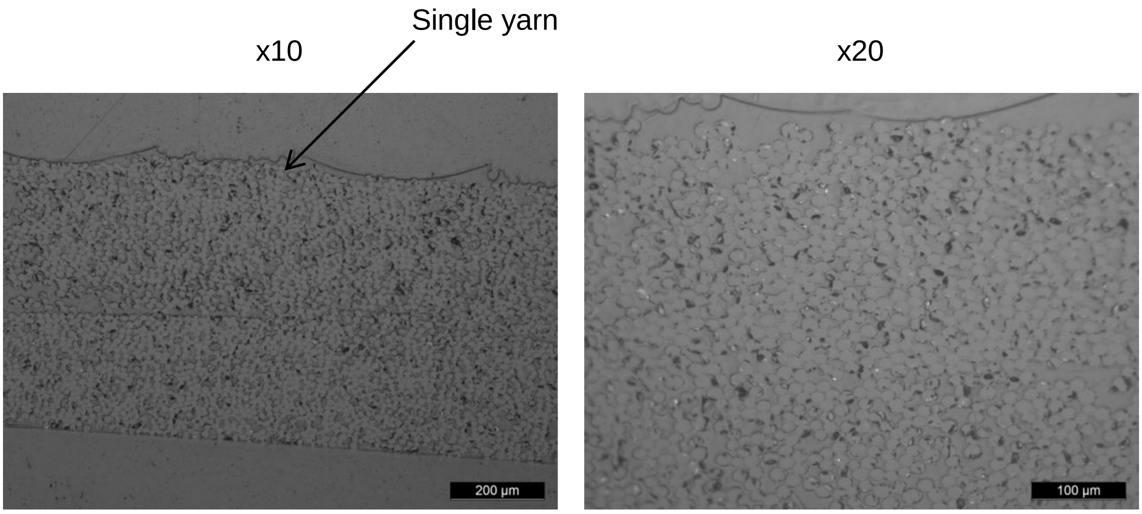


Figure 4.4: Pillar 2mm. Objective: x10 (left). Pillar 2mm. Objective: x20 (right)

The black zones indicate that some of the fibers are been damaged during the preparation of the specimens to embed because of smoothing.

4.1.3 Sample 3

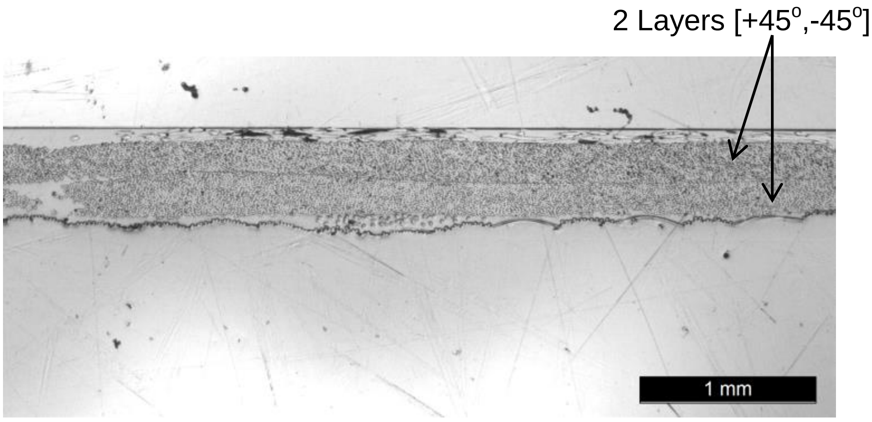


Figure 4.5: Plain 6mm, direction A. Objective: x2.5

The real width in this specimen is equal to 0.59 mm.

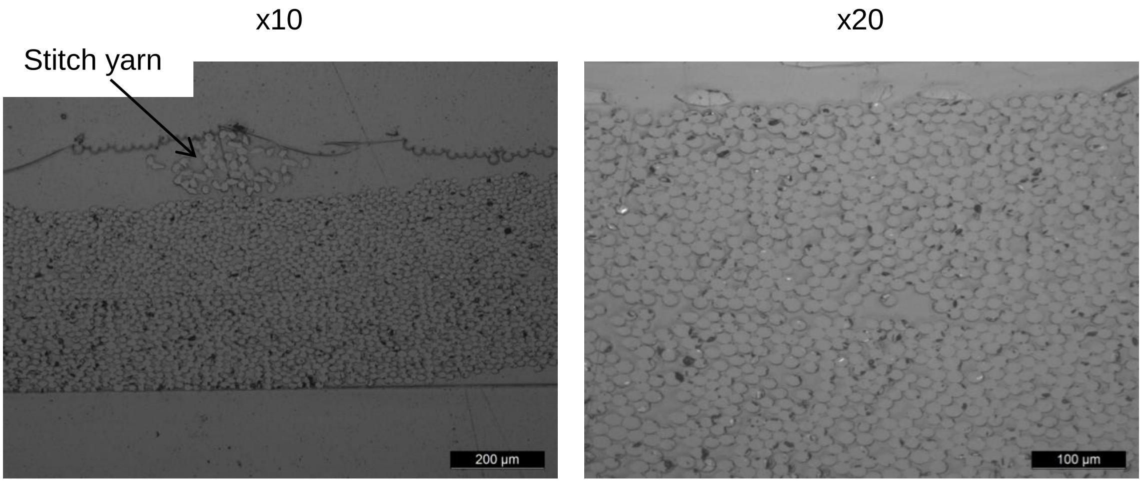


Figure 4.6: Plain 6mm. Objective: x10. (Left) Plain 6mm. Objective: x20 (right)

4.1.4 Sample 4

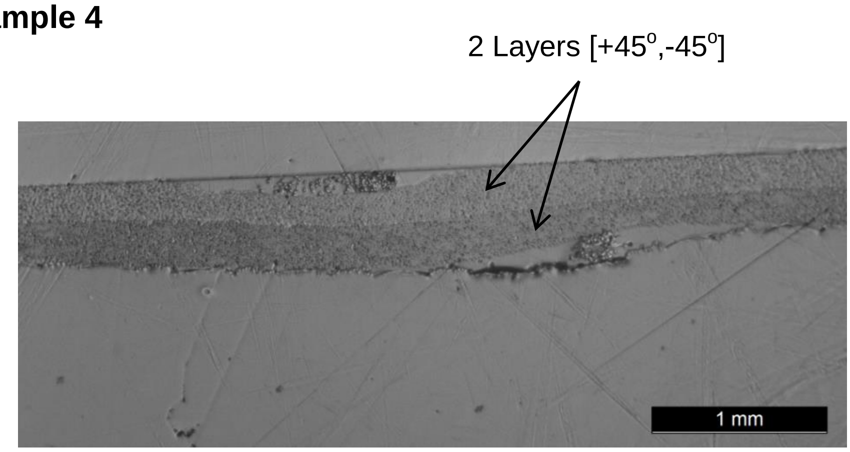


Figure 4.7: Plain 6mm, direction B. Objective: x2.5

For the last specimen the real width is 0.48 mm.

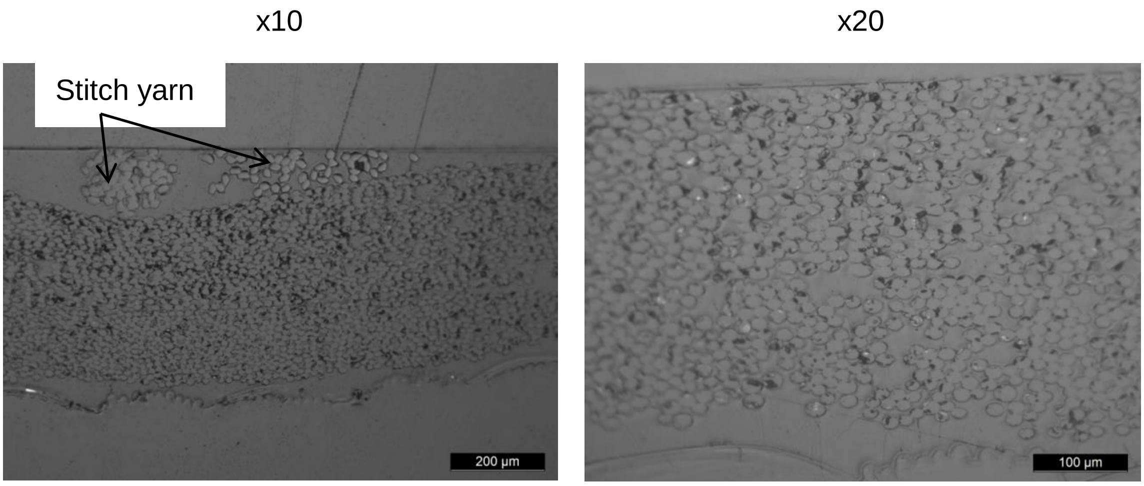


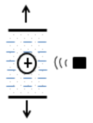
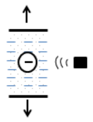
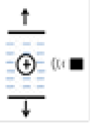
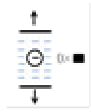
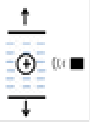
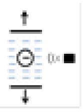
Figure 4.8: Plain 6mm. Objective: x10(left). Plain 6mm. Objective: x20(right)

4.2 Mechanical test

Before showing the results for the bias extension test, an overview for the analyzed samples is appropriate. Thus in table 4.2 there is a summary for the different samples.

The samples with a cross are ready for the test but problems occurred for the other samples during the preparation or during bias extension test. Thus, these fabrics are not able to take into consideration for analysis.

Table 4.2: Overview samples for bias extension test

Characteristics / Sample	EBC min.		EBC normal		EBC max.	
						
Pillar 4 mm			X	X	X	X
Plain 2 mm	X	X				
Plain 4 mm	X	X			X	X
Plain 6 mm	X	X	X	X		

The samples were damaged in the previous steps

The samples were damaged in the bias extension test

Four different relations for each sample have been analyzed because these are the most relevant for the industry applications.

- Effective distance vs. Effective force
- Theoretical angle of shear vs. Standard shear force
- Theoretical angle of shear vs. measured angle of shear
- Measured angle of shear vs. standard shear force

Experimental set-up and data evaluation

Normalization of data depends on sample shape, size, shear distribution, and boundary conditions. Shear distribution and boundary conditions are primarily affected by the test method, whereas size and shape are factors that also affect same-method tests.

The textile samples have a width of b_{BE} =100 mm and a length of l_{BE}= 200 mm. The angle θ of the shear is to start of test 90°, since biaxial fabrics are tested with the lay-up ±45°.

For better introduction of force and defined starting position both samples ends are fixed wide clamps in 10 cm, which are clamped in the material testing. Before applying the normalization method, a comparable state of stress must be present. Before considering an initial force F is applied to a pre-load of 1 N and with negative shear is selected a lower initial force of 0,5 N as significantly lower maximum shear forces occur in this knitting yarn orientation in the exam. We then the fabric sample 50 mm/min charged at a constant test speed con on train. The measured test force F is recorded over the Effective distance d_y [mm].

The data are used to calculate from the measured angle of the fiber orientation β(t) by equation 4.1 the real shear angle α(t) for predefined time steps.

$$\alpha(t) = 2 \cdot \left(\beta(0) - \beta(t)\right) \tag{4.1}$$

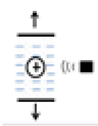
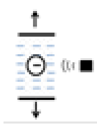
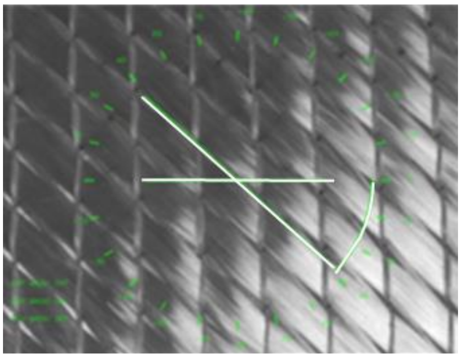
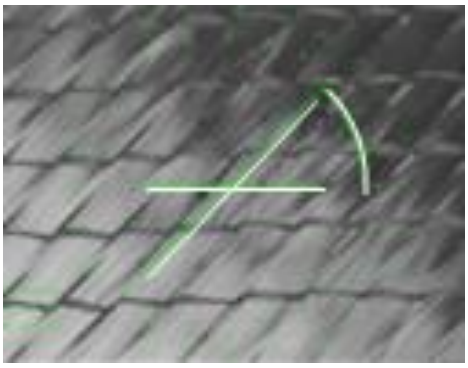
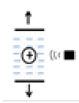
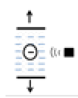
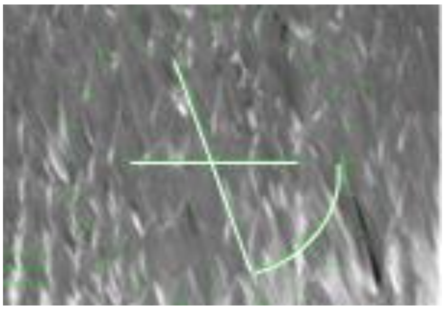
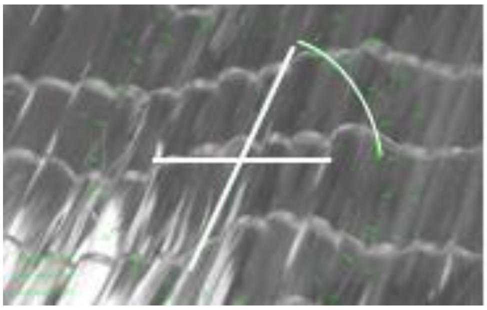
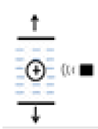
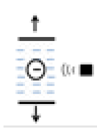
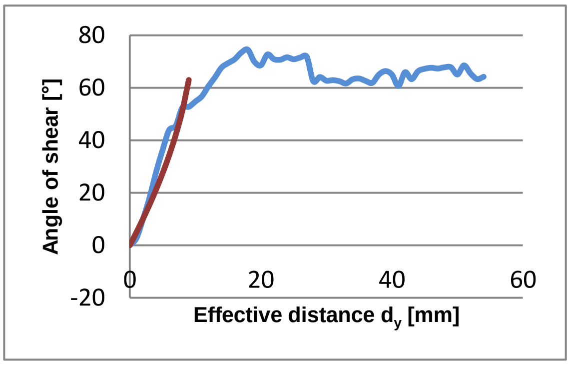
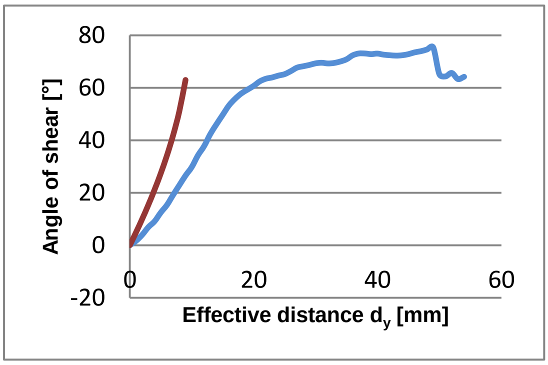
For a better and more effective compression of the results, they are divided in four groups:

- Group 1: Plain ±45 6mm EBC min. and normal.
- Group 2: Plain ±45 4mm EBC min. and max.
- Group 3: Plain ±45 2/4/6 mm EBC min.
- Group 4: Pillar ±45 4mm EBC max. and normal.

Thus in the following tables the results are shown and commented. The graph shows the parameters during the bias extension test after that the data have been processed with Matlab tool.

Table 4.3 shows the results of optical measurement with photo camera and AVS-System for the sample Pillar / 4mm / EBC normal. The blue line (measured angle of shear) in the graph of AVS measurement describes the average of five continuous series of sample. The optical measured results show that in negative shear a significant difference be-tween theoretical shear angle ϒ and the measured with the AVS system shear angle α exists.

Table 4.3: Example measurement with the AVS-System in bias extension test for the sample Pillar / 4mm / EBC normal

$\boldsymbol{\beta}\ (\boldsymbol{t}=\mathbf{0})$	
	
	
$\boldsymbol{\beta}(\boldsymbol{t})$	
	
	
Measured angle of shear α (mean) Theoretical angle of shear ϒ	
	
	

Assumptions and limitations

There are several ways in which the deformations can divergence from the idealized case and this is dependent on many factors including the material, the sample size and ratio.

In first place, care must be taken with lengthways alignment, as this can cause a fairly large apparent discrepancy in the curves, so that it is prudent to ensure that the fabric is not shear and the actual sample aspect ratio is recorded.

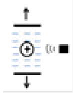
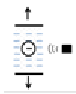
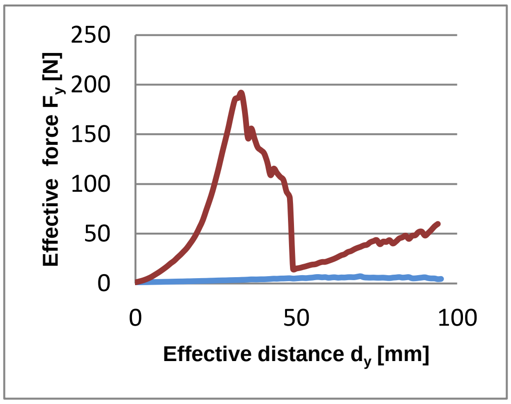
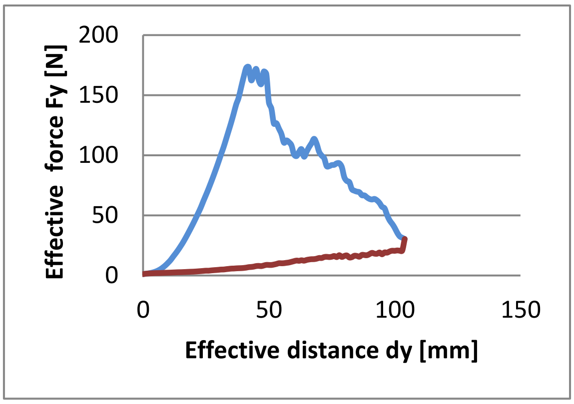
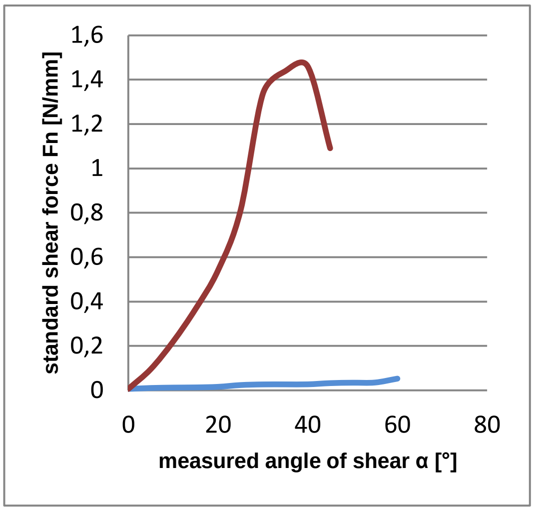
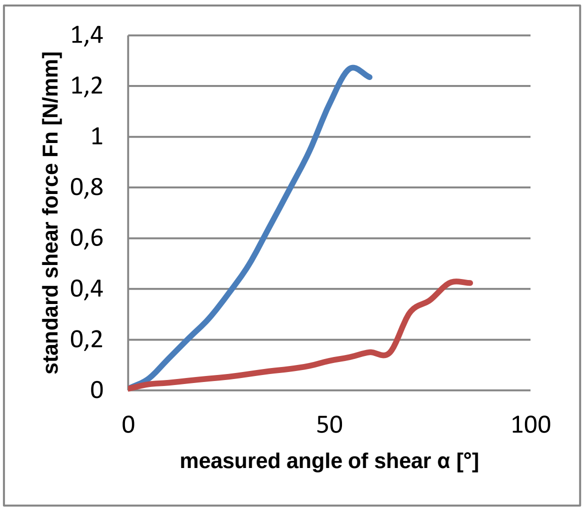
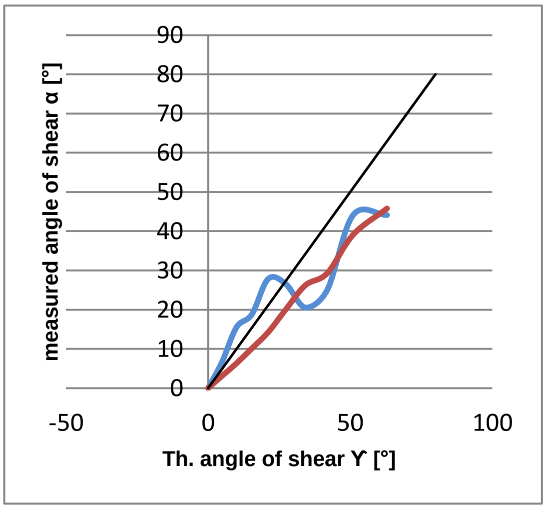
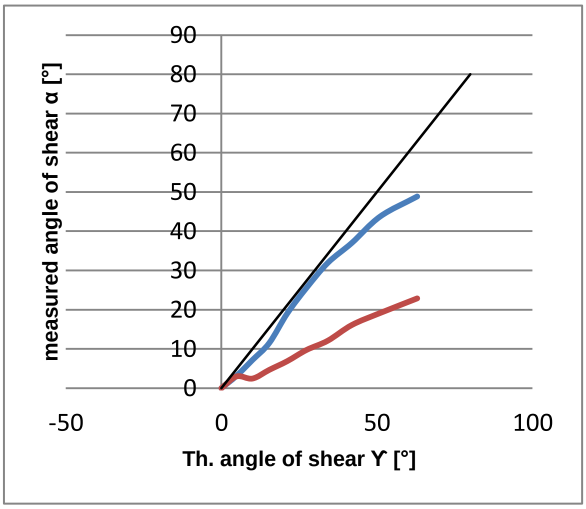
On the other hand, although being relatively impervious to angular misalignment, the response is fairly sensitive to any lengthways misalignment caused while clamping the sample, which alters the sample aspect ratio. The same effect can be caused by any pre-shearing of the material, so that the zero-shear sample ratio is different to the perceived ratio cut out, for example this could be caused during the cutting or the sticking of the carton due to handling. For this reason, such as explain in the previous lines, before the starting of the test pre-load is configured in the machine, so that data is not recorded until the measured load exceeds the set pre-load.

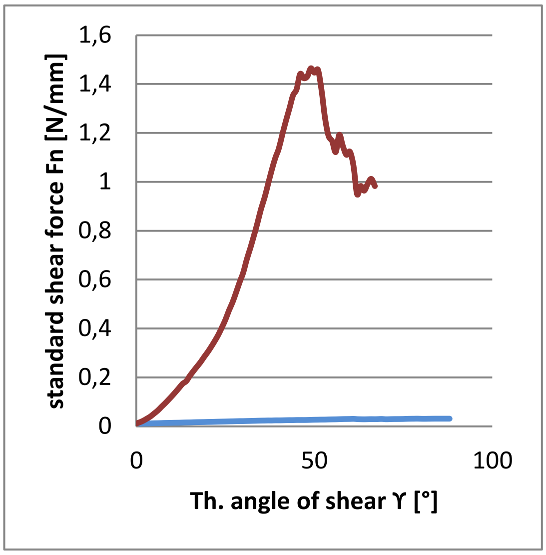
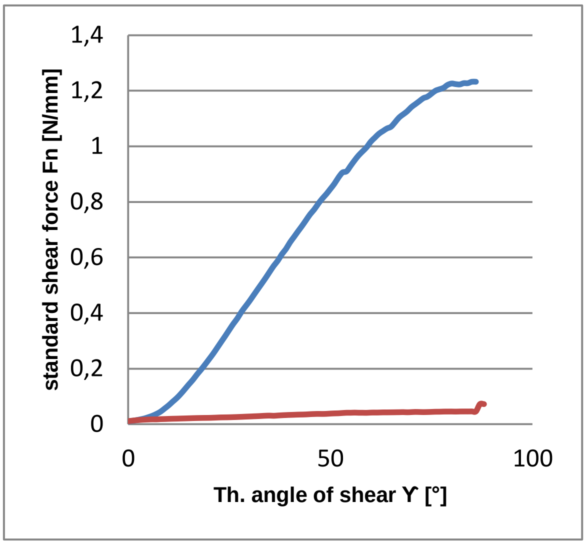
4.2.1 Group 1: Plain 45 6mm EBC min. / normal

There are considerable differences between both samples, not only in the comparison between different EBC values but also between the two different directions of fibers orientation.

First the samples for the positive shear show that the values for the sample with higher EBC values, it means less tension of production are significantly higher than the samples with more tension in the production. On the contrary for the negative shear, the values for an EBC lower are higher than the other sample.

Table 4.4: Group 1: Plain 6mm EBC min. / normal

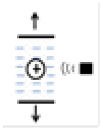
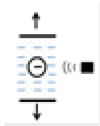
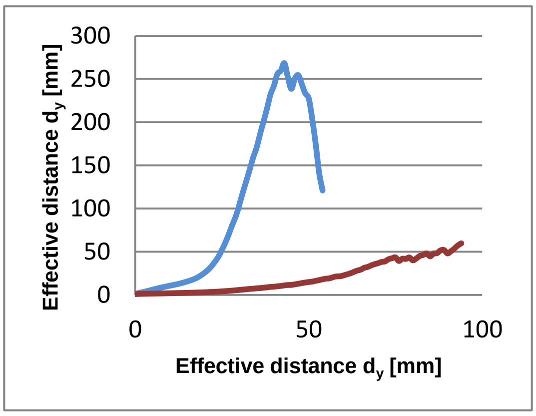
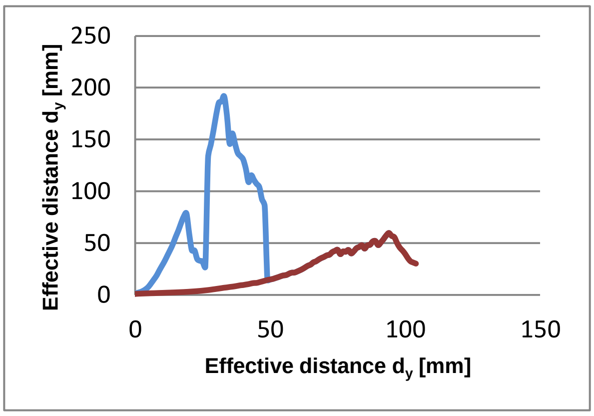
Plain 6mm EBC min. Plain 6mm EBC normal	
	
	
	
	

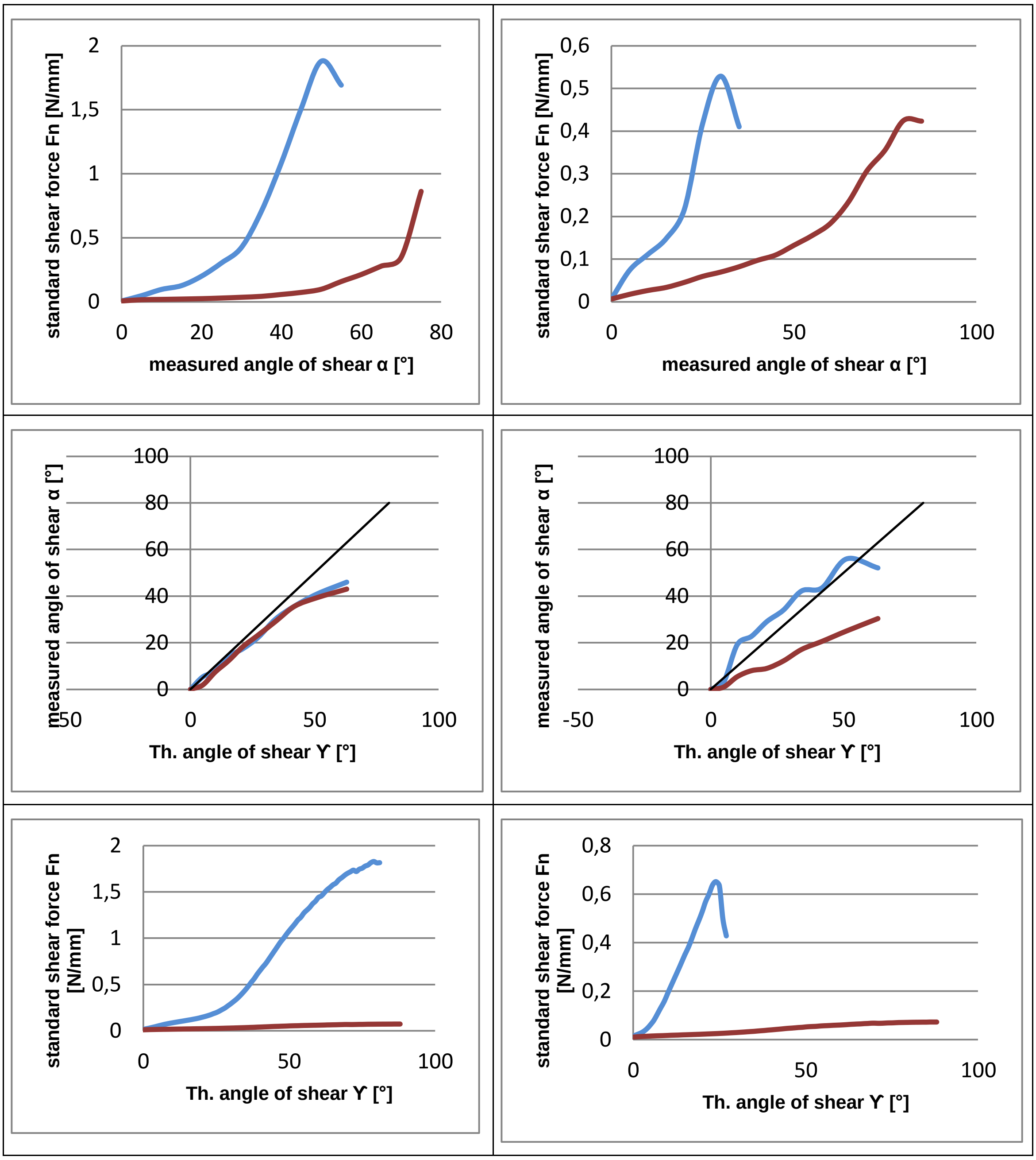
	

4.2.2 Group 2: Plain 4mm EBC min. and max.

For these groups the samples still showed a large deviation between each other but in this case the values for the sample with EBC minimum are always higher that the values for the other sample regardless of the direction of sample is not significant.

Table 4.5: Group 2: Plain 4mm EBC min. and max.

Plain 4mm EBC min Plain 4mm EBC max	
	
	

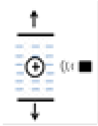


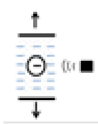
4.2.3 Group 3: Plain 2/4/6 mm EBC min

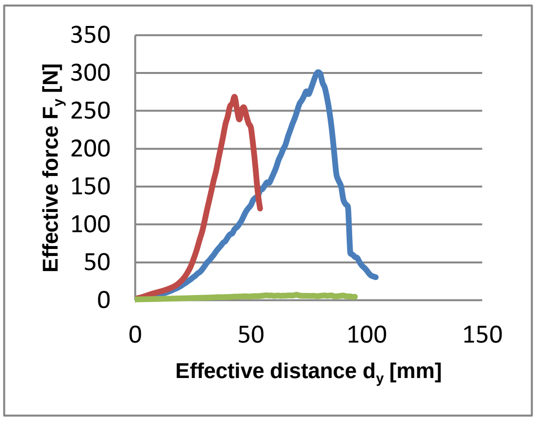
In this case, the groups consist in three samples with different stitch length. The results are very heterogeneous and only when the theoretical angle of shear is compared to measured angle d shear similar values are observed.

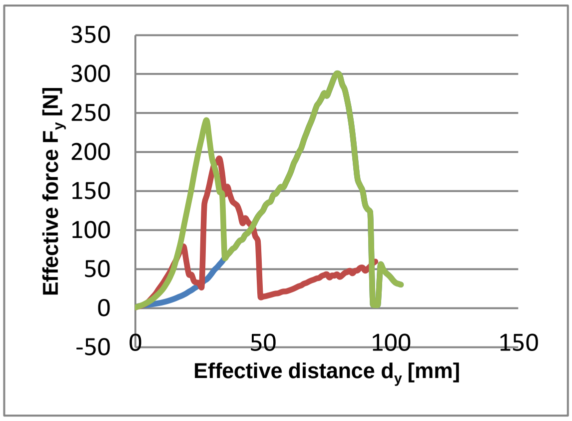
Table 4.6: Group 3: Plain 2/4/6 mm EBC min

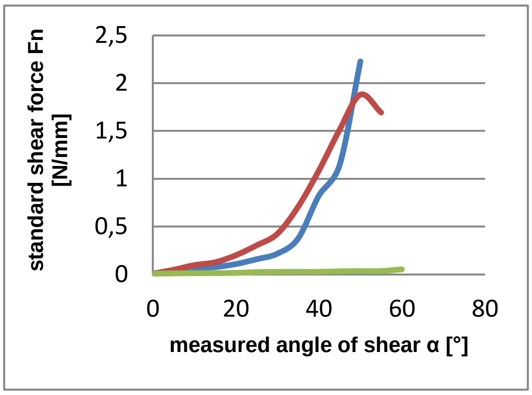
Plain 2mm EBC min
Plain 4mm EBC min
Plain 6mm EBC min

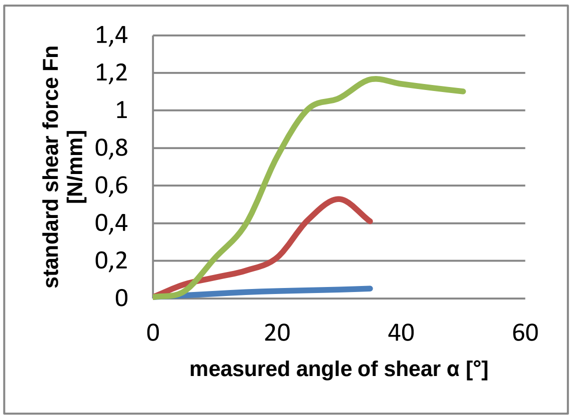


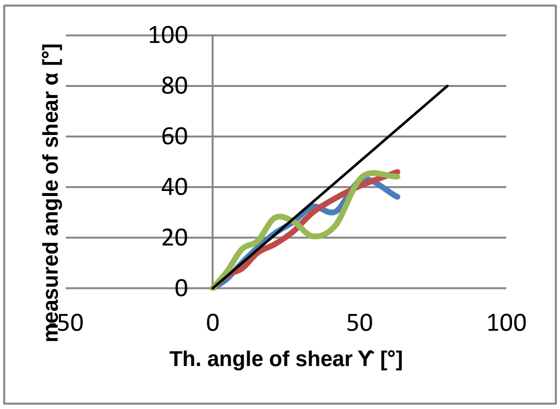


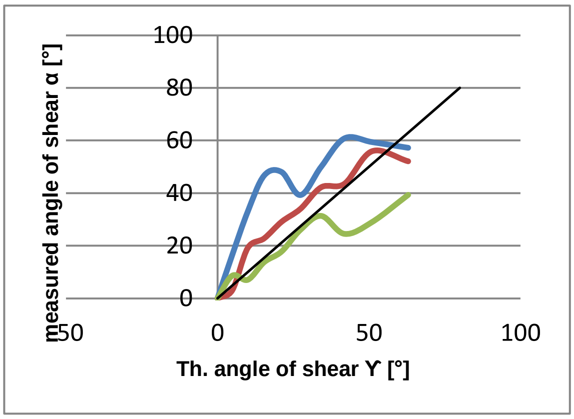


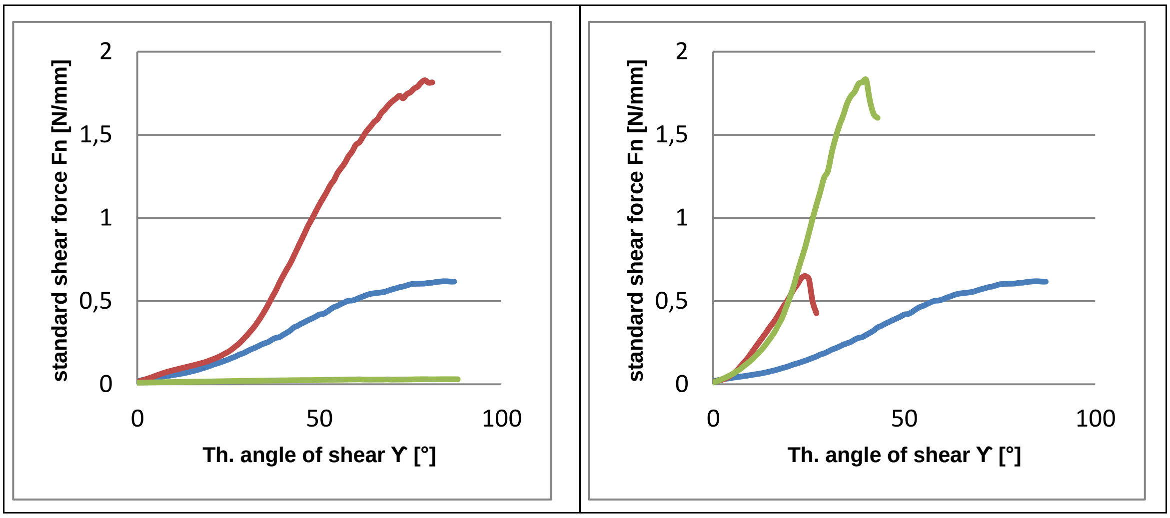








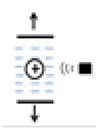
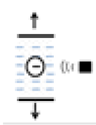
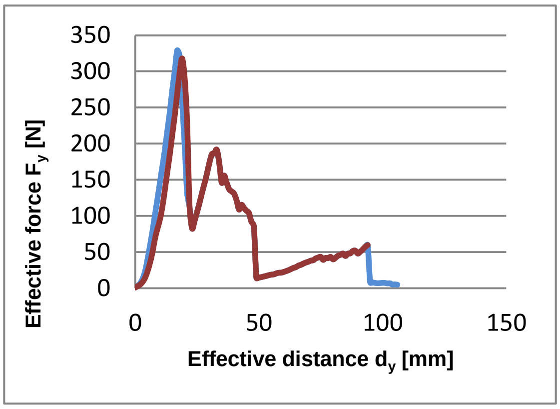
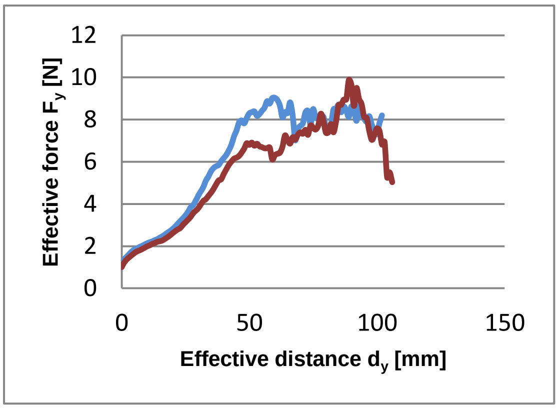




4.2.4 Group 4: Pillar 4mm EBC max. and normal

For this group, pillar with stitch length of 4 mm and different EBC values is compared. Like it can be observed, the values are more similar that in previous groups. For both samples the results fluctuate in a small range and it can cause analogous final properties.

Table 4.7: Group 4: Pillar 4mm EBC max. and normal.

<table>
<tr><td>Pillar 4mm EBC normal
Pillar 4mm EBC max.</td><td></td></tr>
<tr><td></td><td></td></tr>
<tr><td>
</td><td>
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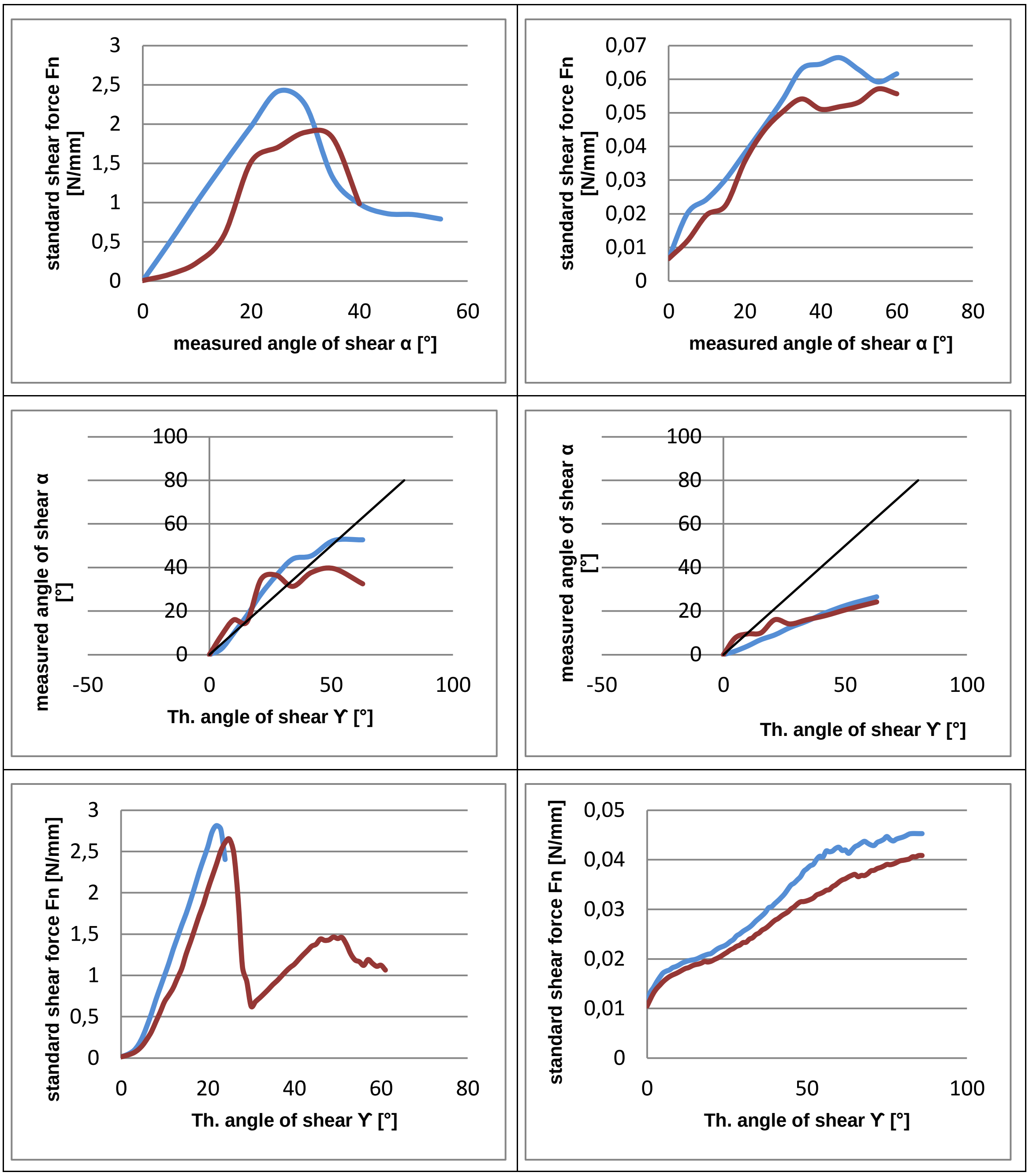

standard shear force Fn [N/mm]
measured angle of shear α [°]
standard shear force Fn [N/mm]
measured angle of shear α [°]
measured angle of shear α [°]
Th. angle of shear ϒ [°]
measured angle of shear α [°]
Th. angle of shear ϒ [°]
standard shear force Fn [N/mm]
Th. angle of shear ϒ [°]
standard shear force Fn [N/mm]
Th. angle of shear ϒ [°]

5 Conclusions

In this chapter the conclusions are described from the results. A general idea of the possible causes and solutions is discussed in order to improve the results. The chapter, such in the previous chapters. First the conclusions from the microscope are commented paying attention to the differences between the stitch.

In the second part, the conclusions from bias extension test are mentioned in the differences between the types of weave, tension and stitch length with the help from graphics from chapter 4.2 and focussing on the angle of shear and the force.

5.1 Microscopy

The conclusion can be based on two criteria. The first one is the type of stitch, plain or pillar. And the second criterion is the tension for the stitching. In the following photos, both kinds of stitch are shown.

x10 x20

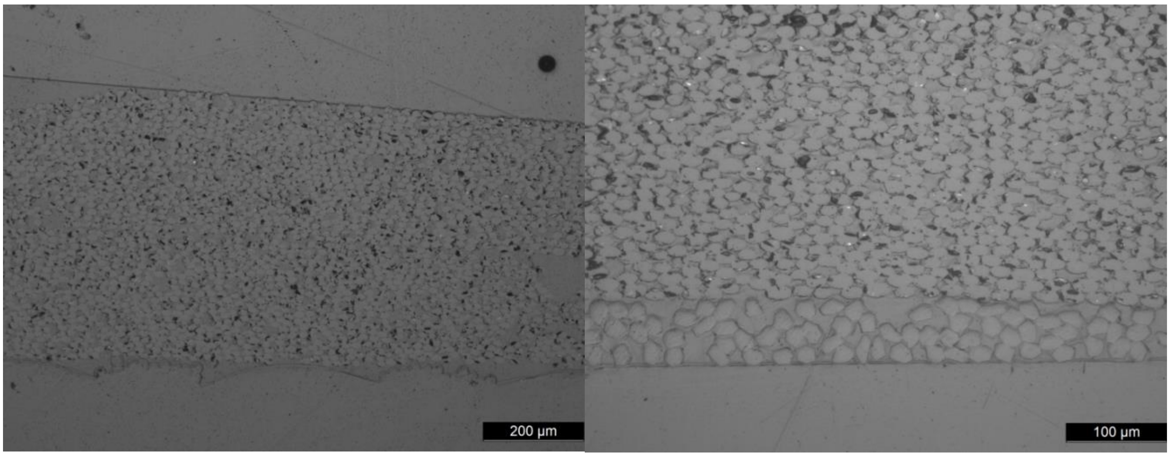


Figure 5.1: Pillar 2mm Objective: x10 (left). Pillar 2mm Objective: x20 (right)

x10 x20

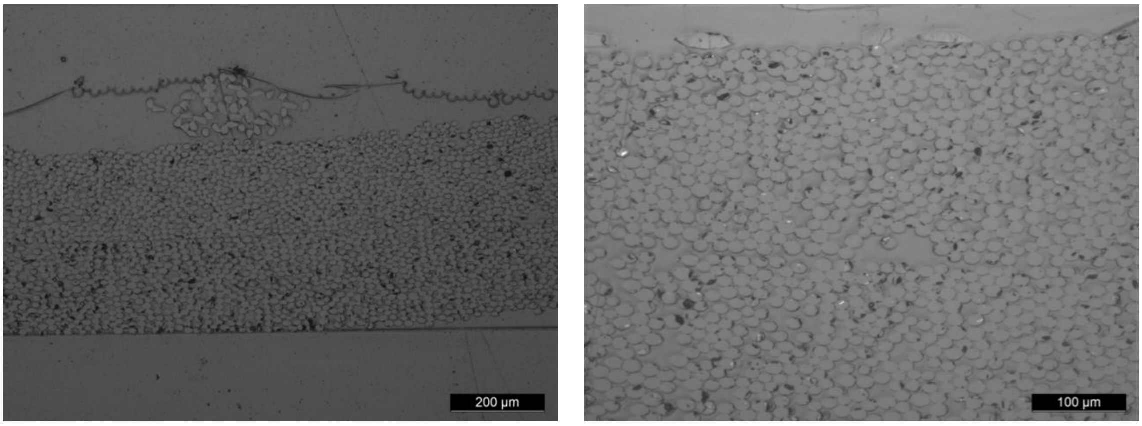
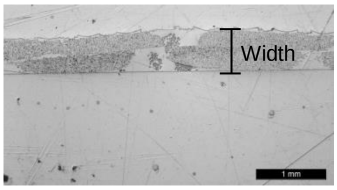
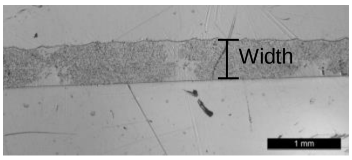


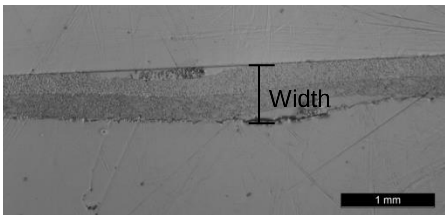
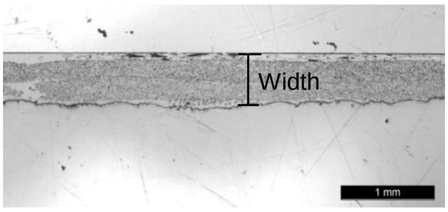
Figure 5.2: Plain 6mm. Objective: x10. (Left) Plain 6mm. Objective: x20 (right)

Looking at the photos, some differences can be observed. For example in the specimens related to plain the two layers can be observed with more clearly and they are more closed (see Figure 5.1). On the other hand the specimens from pillar are more uniform and the two layers cannot distinguish with clarity because the material is not stratified (see Figure 5.2).

Comparing the width, which as calculated in the previous chapter, the following table is obtained:

Table 5.1: Overview from result of calculated width

Sample	Width	Image
Sample 1 (Pillar 2mm)	0.45 mm	
Sample 2 (Pillar 2 mm)	0.57 mm	

Sample	Width	Image
Sample 3 (Plain 6 mm)	0.48 mm	
Sample 4 (Plain 6 mm)	0.59 mm	

In the table, the different width is shown. As a conclusion the variance between the samples in different directions must be cited. The widths of samples with direction B are thinner than the widths in direction A.

In order to find clearer conclusions maybe different ways to analyze the specimens with the microscopy will be better. For example a view of the whole specimen, not only the up surface, could be important to determine the deformation for the stitch length or for a better observation of the stitching.

To determine a proper tension of the fabrics it is recommended to analyze different EBC values and compare the different widths. This can be a starting point to future investigations to find resistant fabrics.

5.2 Bias extension test

As is it explained in the previous chapter, the results are divided in four groups in order to get a clearer overview.

Within all the data results, the most significant results are analyzed in depth because they are the result with more influence in the industry

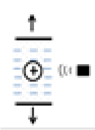
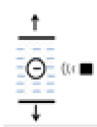
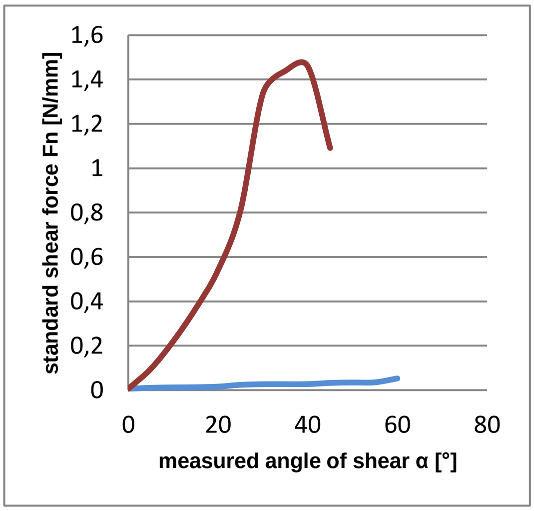
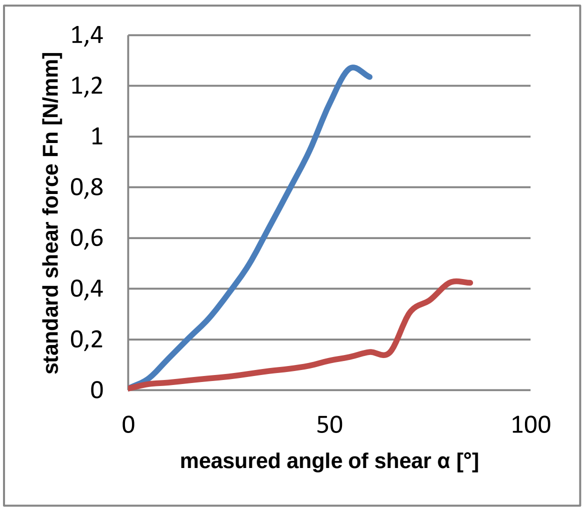
5.2.1 Group 1: Plain 6mm EBC min. / normal

Like in the previous chapter, for these samples exit a striking difference between the values. With positive shear the maximum standard force of shear is considerably bigger for the sample with EBC normal. The line for this sample has a big gradient to the maximum while the line of the other sample has a moderate growth. On the contrary, in a negative shear test, the maximums values are for the sample with EBC value minimum.

If the second graph is observed, where the measured angle of shear is compared with the theoretical angle, the differences are fewer. In a positive shear test, the measured angle of shear has not a uniform growth. It can be caused because the angles measured appear to be subject to a lot of noise. For both lines, when the angle is bigger, more is the divergence with the linear relation.

In the negative shear test for sample with EBC value minimum, the variation between the linear relation of angles and the angles of shear is lower. It can be caused because the EBC values are smaller and it means that the tension during the production is higher, thus the fibers are more fixed and it bring involves a lower deformation of the fibers orientation.

Table 5.2: Group 1: Plain 6mm EBC min. / normal

<table>
<tr><td>Plain 6mm EBC min.
Plain 6mm EBC normal</td><td></td></tr>
<tr><td></td><td></td></tr>
<tr><td>
</td><td>
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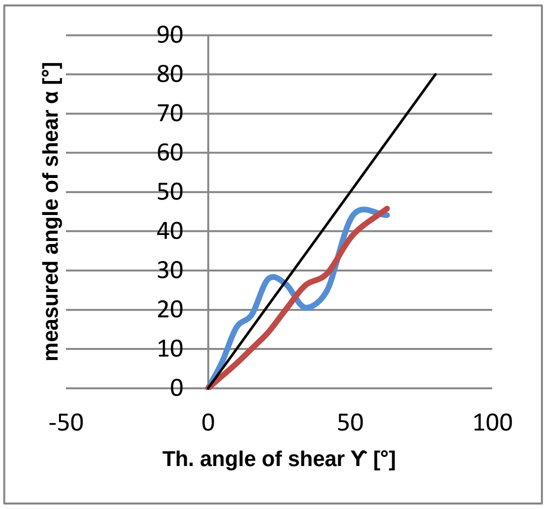
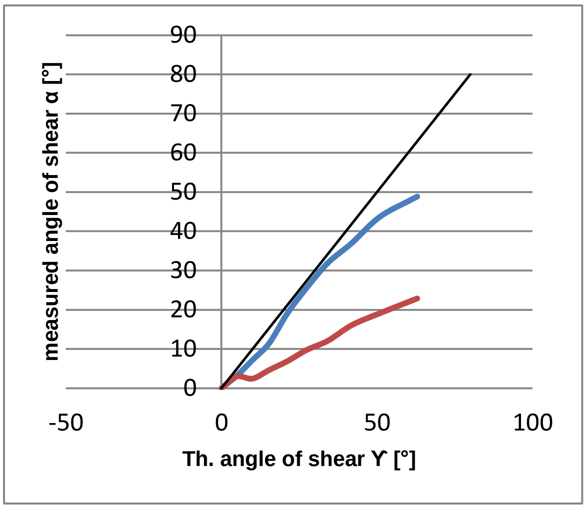


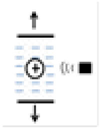
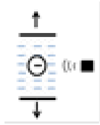
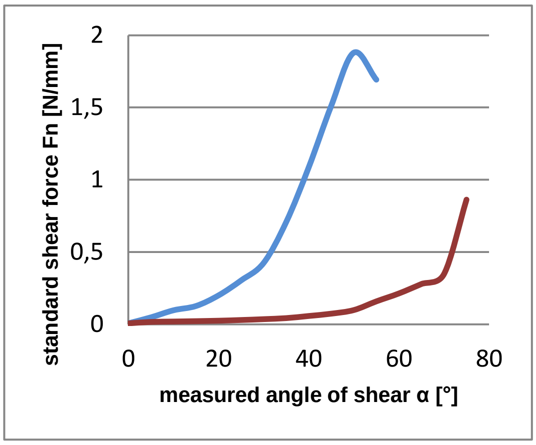
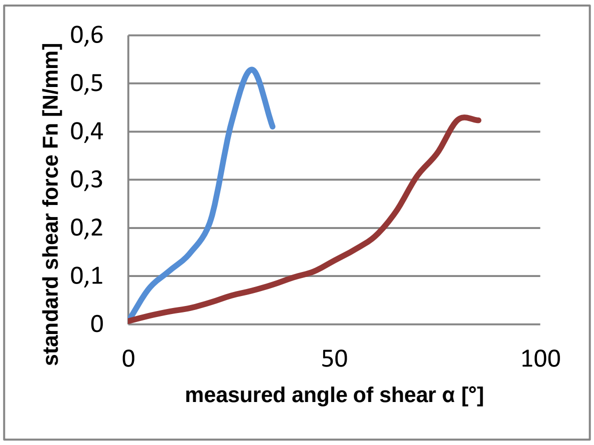
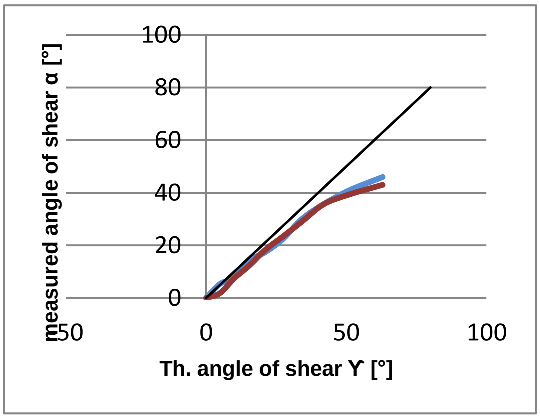
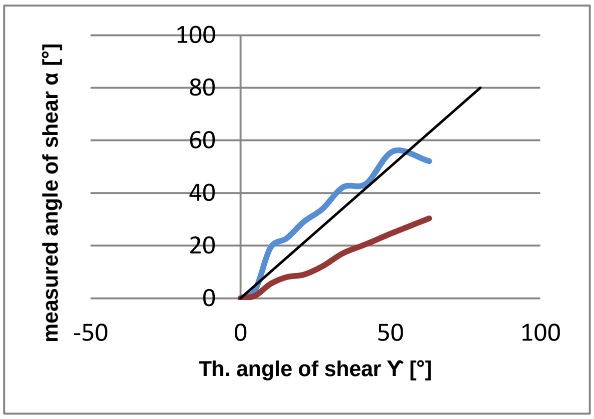


5.2.2 Group 2: Plain 4mm EBC min. and max.

In this group, consists is also in plain but now the stitch length is 4 mm and the EBC minimum and maximum are compared. For both tests, positive and negative shear, the maximum force of shear is reached for the sample with EBC value minimum but these values are achieved further that in the other sample, where the gradient is lower. It implies that when the tension in the production is higher, a bigger force of shear is demanded to obtain the same angle measured of shear. It indicates that the EBC value high produces compacted layers and for this reason the angles needs more force for deformation.

If the relation between the angles is observed, similar values are obtained for the positive shear. The results begin to be worse when the angles rise 40°. On the other hand, in the negative shear test, the values are more divergent. The relation of angles are above the linear relation for the sample with EBC minimum while for the EBC maximum the values are under the line of linear relation. This involves that a bigger tension produces that the measured angle of shear is bigger than the theoretical angle of shear. On the contrary, for an EBC value maximum the measured angles are lower.

Table 5.3: Group 2: Plain 4mm EBC min. and max.

Plain 4mm EBC min Plain 4mm EBC max	
	
	
	

5.2.3 Group 3: Plain 2/4/6 mm EBC min

The results presented here are chosen to highlight the advantages and disadvantages of samples with different stitch length. The results are opposed between positive and negative shear tests. For the first of them, a bigger force is needed to reach the same angle of shear for the sample with smaller stitch length. This is contrary in a negative shear.

In relation to angles there are different behaviours for each stitch length. The blue line (2 mm) show that the results since 35° hasn't deviation and the measurement is identical as the calculated angles. For the stitch length of 4 mm,when the angle is lower than 15º the results are linear but then exits a deviation around 8º, which is upper when the angles increase. Finally in the red line (6mm), the measured angle is bigger than the theoretical angles until 30º and then for raised angles, the relation is opposed.

It means that the smaller stitch length causes better bindings for the fibers that bring lower divergences between the measurement angles and the expected angles.

Table 5.4: Group 3: Plain 2/4/6 mm EBC min

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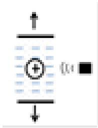
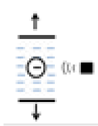
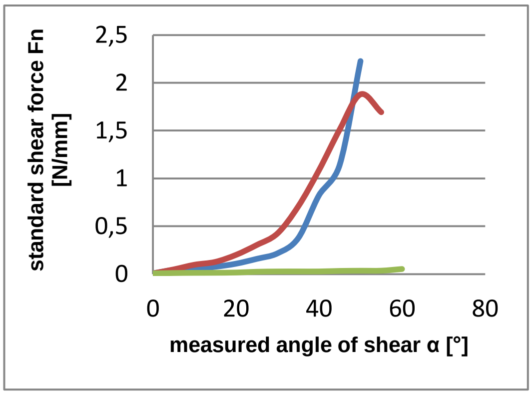
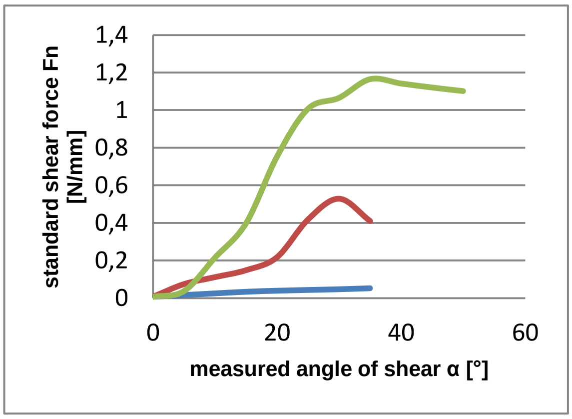
<tr><td>Plain 2mm EBC min
Plain 4mm EBC min
Plain 6mm EBC min</td><td></td></tr>
<tr><td></td><td></td></tr>
<tr><td>
</td><td>
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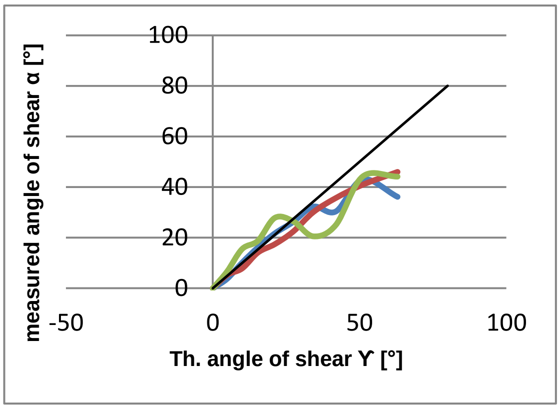
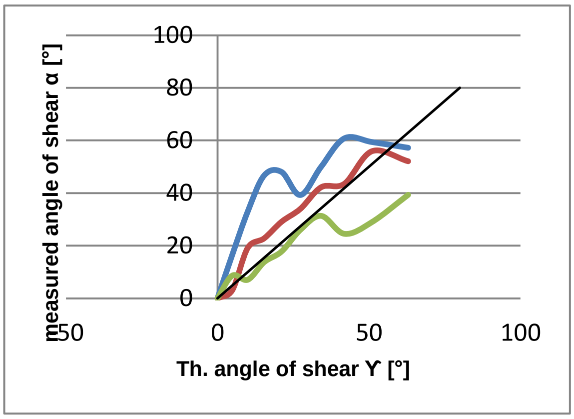
<tr><td>
</td><td>
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5.2.4 Group 4: Pillar 4mm EBC max. and normal

In this group other kind of weave is analyzed; pillar.

In this case the results are more analogous for both EBC values. The forces are bigger for positive shear test as a consequence, the resistance will be better. The tests appear to be relevant for the positive shear because in the other case the results show an important divergence since 15º. From this point, the measured angles are lower than theoretical values

Table 5.5: Group 4: Pillar 4mm EBC max. and normal

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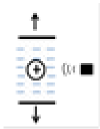
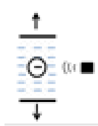
Pillar 4mm EBC max.</td><td></td></tr>
<tr><td></td><td></td></tr>
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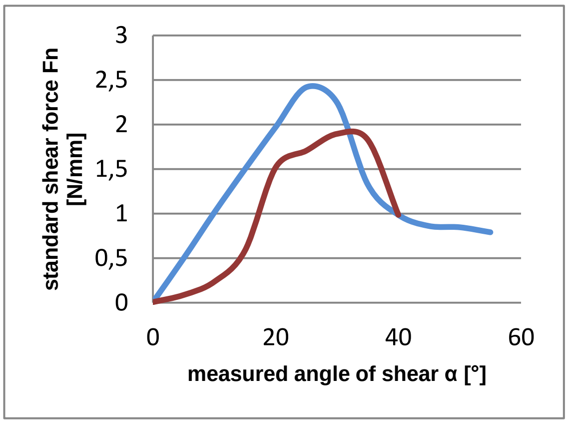

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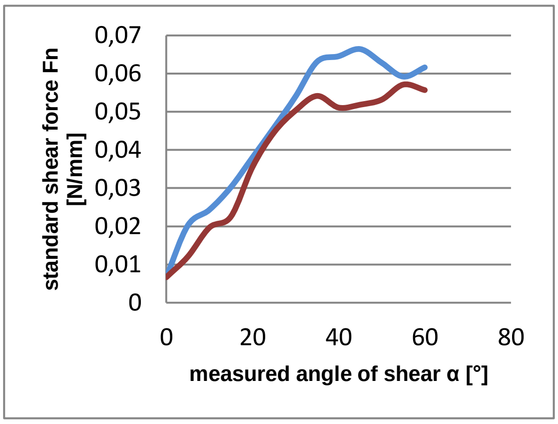

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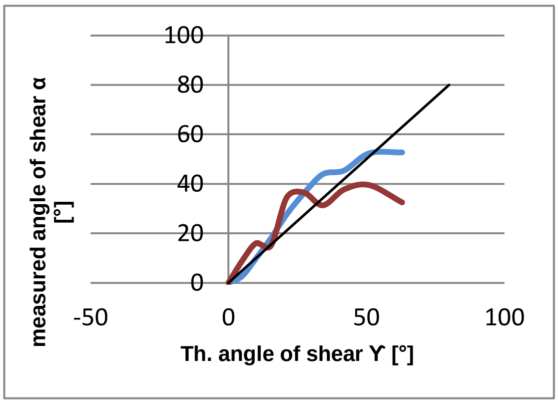

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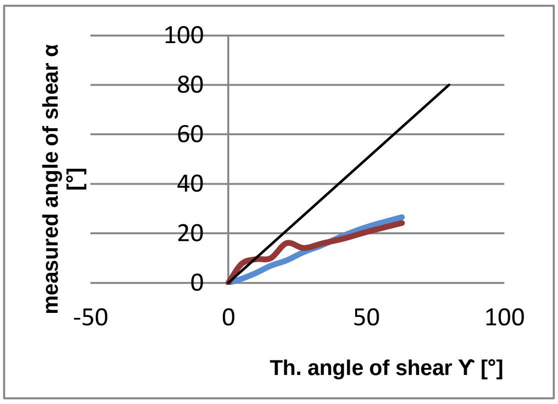

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6 Summary and Outlook

The conditions of uniform high quality non-crimp fabrics (NCF) for technical applications are dependent for various parameters. Pattern type, stitch length and warp yarn tension are some of this parameters and they are decisive for the properties of the fabric. On the basis of experiments done on the warp knitting machine Copcentra MAX 3 CNC, these specifications have been changed for producing the fabrics for testing.

The plan of work is based on two different methods for analyzing the samples. In order to make clearer the process, the following table shows an outline.

Table 6.1: Outline of sample and methods

Weave	Stitch length	Layer	EBC value	Method
Pillar	2 mm	-45º/+45º	Minimum	Microscopy
	4 mm	-45º/+45º	Normal / Maximum	Bias extension test
Plain	2 mm	-45º/+45º	Minimum	Bias extension test
	4 mm	-45º/+45º	Minimum / Maximum	Bias extension test
	6 mm	-45º/+45º	Minimum	Microscopy
			Minimum / Normal	Bias extension test

For the microscopy, Microscope Leica DM 4000M is used to obtain the results. As a conclusion for this test the most notable is the differences between the pattern types. The layers in the sample of plain are more closed and on the other hand the samples of pillar are more uniform. The closed layers could influence in a deformation of the fibers to obtain more homogeneous results.

The bias extension test is carried out with ZWICK Z100 testing machine of Zwick GmbH & Co. KG, Ulm. The relation between different parameters is analyzed with the help of Apodius systems. The evaluation and data interpretation is performed with the application Excel and a Matlab tool. The results shown that the variance of the EBC values and stitching length imply divergences between the values. Maybe the better results have been obtained with the sample of plain 2/4/6 mm with EBC min and with Pillar 4mm EBC max. and normal, all of them with positive shear test. In these cases, the measured angle of shear is similar to theoretical angle of shear.

Take as a starting point this work, the future investigation could broaden more variance of the parameters in the production of the fabrics. At beginning more different fabrics have been produced but not all of them were able to analyze. This occurred for various reasons, such as due to a lack of time or because some of the sample were damaged during the process. Nevertheless, the analysis of more samples with different stitching length will be significant to obtain clearer conclusions about the influences in the mechanical properties.

Other field of investigation could be based on the analysis of sample with three layers and the comparison of the properties between them because of they have different weight and this characteristic is an important restriction in applications like automotive and aerospace.

7 References

[Anu09] Dhyani Anupam

VARTM Process With Some Modifications

Michigan State University,2009

[Apo15] Apodius GmbH

AVS metrology solutions. Apoduis Camera

Apodius GmbH 2015

[Ass] Assyst bullmer, intelligent solutions

TURBOCUT S 2501 CV

Assyst Bullmer Ltd. United Kingdom

[GVW15] Gries, Thomas; Veit, Dieter; Wulfhorst, Burkhard

Textile Technology, An introduction. 2nd Edition. Hanser

Hanser Publications, Cincinnati,2015.

[HWL08] Harrison, P. ; Wiggers, J. ; Long, A.C.

Normalisation of shear test data for rate-independent compressible fabrics

University of Glasgow. Glasgow ePrints Service. 24th October 2008

[ITA] Institut für Textiltechnik

RWTH Aachen. Aachen

[Kri15] Helga Krieger

Methode zur Auslegung von Gelegen mit local angepassten Fertigungdparametern für Hochleistungs-Faserverbundkundtstoffe

Aachen, RWTH, Fakultät für Maschinenwesen,2015

[Lei03] Leica microsystems

Leica DM4000 M

Leica Microsystems Wetzlar GmbH. Germany, 2003

[Lib10] LIBA Maschinenfabrik GmbH ; American LIBA Inc.; China LIBA Limited

Copcentra MAX 4 CNC,2010

[Lom11] Stepan V Lomov

Non-Crimp Fabric Composites: Manufacturing, Properties and Applications

Woodhead Publishing Limited. Cambridge 2011

Elsevier, 19 abr. 2011 - 544 pages

[LPC+11] W. Lee , J. Padvoiskis , J. Cao , E. de Luycker , P. Boisse , F. Morestin , J. Chen , J. Sherwood

Bias-extension of woven composite fabrics,2011

[Moh04] Krishna Mohan Chittajallu

Computacional modeling of the vacuum assited resin transfer molding (VARTM) process

Clemson University. Mechanical Engineering, May 2004

[PC03] Xiongqi Peng and Jian Cao

BIAS EXTENSION TEST STANDARD

Northwestern University Evanston, Department of Mechanical Engineering,August 2003

[Poh11] Vivienne Pohlen

Analysis of the warp yarn tension on a warp knitting machine with multiaxial weft insertion on the basis of online tension measurements

RWTH Aachen. Aachen. Institut für Textiltechnik.,2011

[PPG15] PPG Fiber Glass

Direct roving fiber glass HYBON 2011

HYBON® 2001 Fiber Glass Boletín del producto_04_2015

[www15] http://www.saertex.com/en/products/multiaxial-fabrics/glass-carbon-aramid

SAERTEX GmbH & Co.KG, Access: 01.07.2015

[www15a] http://www.themoldingblog.com/2015/07/28/new-sensor-system-boosts-qc-on-cfrp-parts/

New Sensor System Boosts QC on CFRP Parts

Access: 01.07.2015

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