Fiber fraction in woven structures

Willy Ignatius

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Abstract:

The purpose of this thesis is to study the effect on fiber volume fraction due to yarn-spacing in fiber-reinforced composites. Fiber volume fraction is the fractional amount of fiber in a composite. The volume of fiber as compared to the total volume. This subject is relevant to composite engineering due to the rule of mixtures. The rule of mixtures is used to estimate properties such as elastic modulus. Using the rule of mixtures requires the value for fiber volume fraction. The study was done by modelling textiles that are commonly used as reinforcing materials for composites. The modelling was done with a 3D design software called Soldiworks. Since SolidWorks is not commonly used for this type of work, this thesis also serves as a study for how reliable the method is. The work done for this thesis can be categorized into three subject areas. Analytical calculations for textiles that are suitable for it, modelled results and microscopic images of ready composites. The analytical results are compared to the modelled results of the same textile types and are proven to be identical. This shows that modelling gives accurate results. All modelling results are presented with the same variance in yarn-spacing. One major determination was done when analyzing the modelled results. It appears that fiber volume fraction is largely affected by the number of interlacements between yarns. The microscopic images were taken and analyzed to get an understanding if the modelled textiles represent what one finds in practice. It appears that in practice, textiles are very unpredictable and properties such as yarn thickness, yarn cross-section etc. are never constant. It seems that the method used in this thesis is reliable for studying the effect a certain property has on fiber volume fraction. However, not suitable for predicting fiber volume fraction for any specific composite prior to manufacturing.

Keywords:	Fiber volume fraction, yarn-spacing, rule of mixtures, analytical results, modelled results, microscopic images
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Syftet med detta arbete är att studera effekten trådavstånd har på fiber volymandel. Fiber volymandel är mängden fiber i en komposit. Volymen av fiber i jämförelse med totala volymen. Arbetet är relevant för komposit planering pga. ”the rule of mixtures”. ”The rule of mixtures” används för att estimera kompositers egenskaper, t.ex. elasticitetsmodul. Vid användning av ”the rule of mixtures”, krävs fiber volymandelen. Arbetet förvekligades genom att modellera textiler som används i kompositer. Modelleringen gjordes med programmet SolidWorks som är ett 3D planerings program. Eftersom SolidWorks vanligtvis inte används för denna sorts arbete, fungerar detta också som en studie för hur pålitlig metoden är. Arbetet gjort i detta examensarbete kan indelas i tre kategorier. Analytiska räkningar för textiler som är lämpliga för det, modellerade resultat och mikroskopiska bilder av färdiga kompositer. Analytiska resultaten jämfördes med modellerade resultaten av samma sorts textiler och visades vara identiska. Detta bevisar att modellering ger noggranna resultat. Alla modellerings resultat presenteras med samma variation i trådavstånd. Vid analysering av resultaten gjordes en väsentlig observation. Det verkar som att för varje sammanflätning mellan trådar, ökar fiber volymandelen. Mikroskopiska bilderna togs och analyserades för att studera hur lika/olika modellerade textilerna är i jämförelse med praktiska textiler. Det visade sig att i praktiken är textiler i kompositer väldigt oförutsägbara. Egenskaper som trådtjocklek, trådtvärsnitt osv. är aldrig konstanta. Slutsatsen av detta är att metoden som använts i detta arbete är bra för att studera effekten någonting har på fiber volymandel, men inte en optimal metod för estimering av fiber volymandel för en specifik komposit före produktion.

Nyckelord:	Fibervolym andel, trådavstånd, rule of mixtures, analytiska resultat, modellerade resultat, mikroskopiska bilder
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FOREWORD

I would like to thank René Herrmann for guiding me through this interesting and challenging project. Also, thank you to Oscar Tulander for assisting me with the microscopic images.

LIST OF SYMBOLS AND ABBREVIATIONS

$f = Fiber\ volume\ fraction$

$UD = Unidirectional$

$l = length\ (mm)$

$t = Thickness\ (mm)$

$E = Elastic\ modulus\ (GPa)$

$V = Volume\ (mm^3)$

$m = Mass\ (kg)$

$\rho = Density\ \left({}^{kg}/{}_{m^3}\right)$

$A = Area\ (mm^2)$

$a = Distance\ between\ yarns\ (mm)$

$r = Cross - sectional\ radius\ (mm)$

$p = Yarn - spacing\ (p = {}^{a}/{}_{r})\ (mm)$

1 INTRODUCTION

In composite engineering, fiber volume fraction is one of the most important properties. There are many methods to estimate fiber volume fraction. Fiber volume fraction is the fractional amount of fiber in a composite. The volume of fiber as compared to the total volume. The purpose of this thesis is to study the effect on fiber volume fraction due to yarn-spacing via 3D modelling and to determine the fiber volume fraction of woven textiles as compared to unidirectional ply's.

1.1 Background

Composites are a combination of two or more components. These components can be either natural or synthetic. In a composite the different components do not completely blend, they remain as individual materials that together make up a composite material. Composites are typically designed for a specific use with specific properties required. The materials used in a composite are often chosen to contribute in areas where the other materials are lacking. (CompositesLab, 2016)

This thesis focuses on fiber-reinforced composites. Fiber-reinforced composites are a common type of composite. These composites are made up of a matrix material which is often a polymer and fibers such us glass-fiber. The matrix is responsible of keeping the composite together, protecting the fibers from external damage and transferring the load between the fibers. The fibers provide reinforcing properties such as strength, stiffness and durability. In a fiber-reinforced composite, the fiber is present in form of a textile. The textile is made up of yarns and each yarn is made up of filaments. (CompositesLab, 2016)

The subject is relevant to composite engineering due to the rule of mixtures. The rule of mixtures is an equation that is used to predict properties of composites. The rule of mixtures is mainly used to anticipate the elastic modulus. Calculating an anticipated elastic modulus depends on prediction of fiber volume fraction. Once the fiber volume fraction is known, the rule of mixtures can be used to predict the elastic modulus of the composite.

The rule of mixtures equation that is used to anticipate elastic modulus can be seen in equation 1. (Gürdal, et al., 1999)

$$E_{composite} = fE_{fiber} + (1-f)E_{matrix} \quad \textit{(Gürdal, et al., 1999)} \qquad (1)$$

The theoretic fiber volume fraction can be calculated analytically for some simple cases. Most cases must however be simulated numerically. The fiber volume fraction can be calculated analytically in cases when the yarns are placed in straight lines and are non-woven. Woven textiles are textiles that include interlacements between yarns. Textiles that have unidirectional yarn alignment are an example of non-woven textiles. Textiles that include yarns that are woven or otherwise not placed in straight lines must be simulated numerically. The reason for this is that to calculate the volume of fiber, both the yarn´s cross-sectional area and length must be known (see equation 2). Since the yarns most often have an elliptic form, it is impossible to get an analytic value for the length. A method that is in some cases is used to calculate the length is called “elliptic integral of the first kind”. However, this method is challenging to use. This is where modelling of the textiles is useful. The software allows one to create models of the desired textiles and can be used to obtain a value for the volume of fiber per unit-cell of the composite.

$$V = A * l \qquad (2)$$

1.2 **Objective**

This thesis concerns itself with modelling of textiles that are used in composite engineering. The modelling is done with SolidWorks, which is a 3D design software. These models have been used to anticipate the fiber volume fraction. The aim is to create graphs that describe the change in fiber volume fraction due to yarn-spacing. Yarn-spacing is a property of a textile that largely affects the fiber volume fraction. Yarn-spacing is the amount of space between the yarns.

This thesis also serves as a study of how reliable modelling is for estimating fiber volume fraction. Models of textiles that can be analytically calculated will be done. The results of the models will be compared to analytical results. Microscopic images of composite test pieces are included to study how the models compare to actual composites. These images are also used to describe other important properties of composites.

1.3 Relevant studies

Although there have been many studies of how the fiber volume fraction of a composite affects its properties, I have not been able to find a study that is based on modelling textiles to anticipate the fiber volume fraction. Some studies have used modeling of the fibers in a composite, but the objective of these studies is not relevant to this thesis.

Characterization of Fiber Volume Fraction Gradients in Composite Laminates (Cann, 2008) is a study that used microscopy-based image analysis to measure the fiber volume fraction of a laminate. The aim of this study was to get a better understanding of through-the-thickness fiber volume fraction. As this is not particularly relative to my thesis, I have only reviewed their methods to obtain the value for fiber volume fraction. (Cann, 2008)

Unit cell model of woven fabric textile composite for multiscale analysis (Dixit, 2013) is a study that used unit-cell modelling to estimate in-plane properties of composites. In their study they have used an open source software (TexGen) to create the models, and a finite element software (ABAQUS) to analyze the models. The objective of the study was to get an understanding of how fabric thickness, yarn width, yarn-spacing and fiber volume fraction effects the properties of woven composites. (Dixit, 2013) I have reviewed this study by comparing some of the results that are relative to my thesis.

An Introduction to the Mechanics of 3D-Woven Fibre Reinforced Composites (Stig, 2009) Is a study that concerns itself with investigating the effect on mechanical properties of composites due to what type of textile is used. (Stig, 2009) This study is relevant to this thesis since it includes a discussion of crimp. Crimp is the excess length required of a yarn due to it being woven. Crimp is often expressed as a percentage, which is measured by the length of a yarn while woven compared to the same yarn straightened.

2 LITERATURE REVIEW

This chapter is a review of why fiber volume fraction is important and the most common methods for estimating fiber volume fraction. It is structured by starting with the rule of mixtures and continued by discussing different methods for determining fiber volume fraction. The rule of mixtures is the main reason why fiber volume fraction is important. Fiber volume fraction is a crucial property when implementing the rule of mixtures. The discussion of methods used for determining fiber volume fraction is divided into verifying methods, modelling and estimation via mass and volume properties.

2.1 Rule of mixtures

The rule of mixtures is a method used to estimate the properties of a composite by summation of each materials individual properties based on the individual materials fractional contribution to the volume of the composite. The rule of mixtures can be used for estimation of several properties. For a fiber-reinforced composite, every property that is estimated with the rule of mixtures is based on that the sum of the fiber volume fraction and the matrix volume fraction equals one. (Gürdal, et al., 1999)

In this study the property of interest is the elastic modulus. The rule of mixtures provides an upper- and lower-bound theoretical value for elastic modulus. The upper-bound is a value that corresponds to loading parallel to the fibers (equation 3). The lower-bound value corresponds to perpendicular loading to the fibers (equation 4). (Gürdal, et al., 1999)

$$E_{composite} = fE_{fiber} + (1-f)E_{matrix} \quad \text{(Gürdal, et al., 1999)} \qquad (3)$$

$$E_{composite} = \left(\frac{f}{E_{fiber}} + \frac{1-f}{E_{matrix}}\right)^{-1} \quad \text{(Gürdal, et al., 1999)} \qquad (4)$$

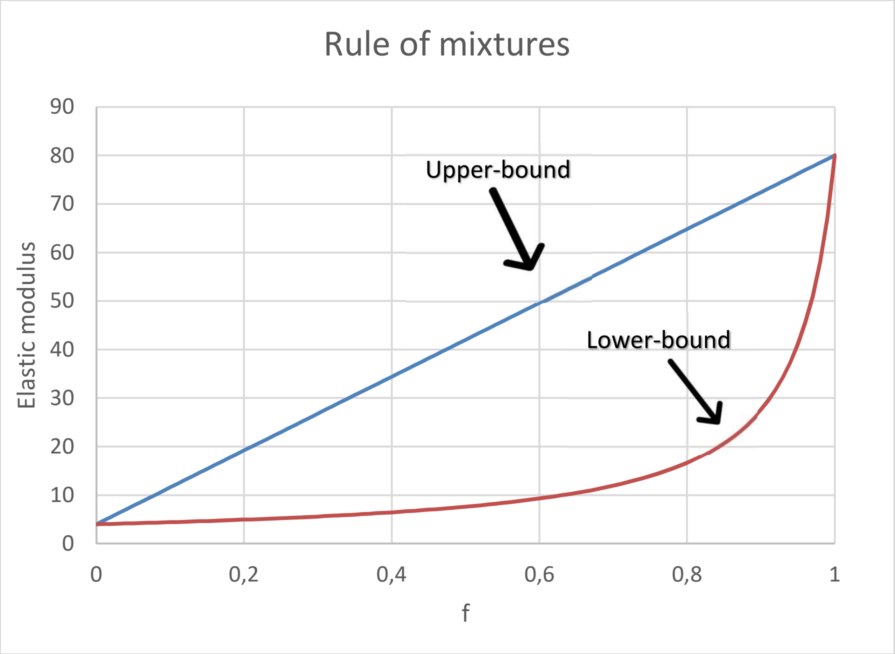

Figure 1. Upper- and lower-bound

As mentioned, the values for upper- and lower-bound elastic modulus are for parallel and perpendicular loading to the fibers. This is only possible with unidirectional fibers. Since textiles often have fiber orientation at 45° for example, the loading will most likely not be parallel or perpendicular. Instead, if the loading occurs parallel to the composites length it will be at an angle of 45°. This would result in a curve lying somewhere between the upper- and lower-bound curve. In other words, for loading that is applied at an angle different to 90° and 0°, the curve for elastic modulus relative to fiber volume fraction will lie between the upper- and lower bound. When predicting the elastic modulus of a composite with reinforcing textile that is not unidirectional, the calculations are done via ABD matrix. The ABD matrix, is a matrix that incorporates the applied loads and associated strains on the composite. Essentially defining the properties of the entire composite. (Gürdal, et al., 1999)

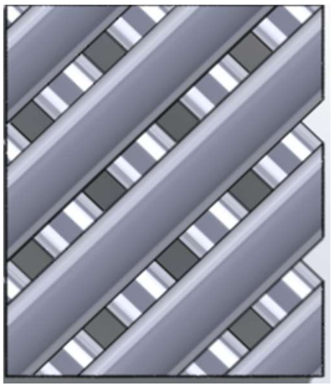

Figure 2. -45/45 non-woven stacked textile

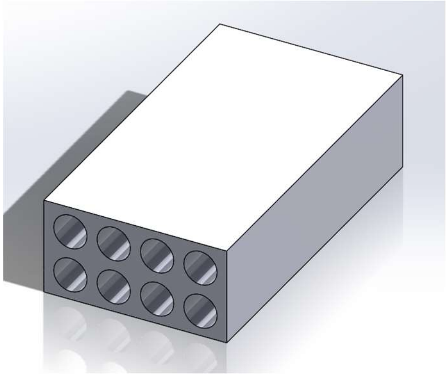

Figure 3. UD non-woven square stacking with matrix material

Fig. 2 illustrates a 45-/45 textile. Meaning that one layer of yarns is at an 45° angle and the other at an $-45°$ angle. With loading parallel to the composites length, the elastic modulus would lie between the upper- and lower-bound. Fig. 3 illustrates a composite piece with UD square stacked textile. The circular parts represent the yarns of the textile and the surrounding body represents the matrix material. With loading parallel to the composites length, the elastic modulus would correspond to the upper-bound limit.

Fiber volume fraction can be determined at a macroscopic- and microscopic scale. At a macroscopic scale, the calculations neglect the possible matrix material within the yarns of the textile. At a microscopic level, it is included. In this thesis, fiber volume fraction is studied at a macroscopic level. Fiber volume fraction is most often a varying property. It is not constant throughout the composite. Since the fiber volume fraction is determined for a unit-cell model, the value is an average of the entire composite. (Schmauder & Mishnaevsky, 2009)

2.2 **Verifying methods**

This chapter discusses the most common methods for determining fiber volume fraction for composites. These methods are also known as verifying methods. They are often used when analytical calculation is not possible. (Zalameda, 2017)

2.2.1 Acid digestion

Acid digestion is one the most common methods for determining fiber volume fraction. It involves removing the matrix material of the composite. The matrix is removed with acid digestion. Once the matrix has been removed the volume of fiber can be calculated the following way (equation 5). (Zalameda, 2017)

$$V_f = \frac{m_{fiber}}{\rho_{fiber}}$$

$$f = \frac{V_{fiber}}{V_{tot}} \tag{5}$$

When performing acid digestion, there is a standard to follow. The standard is ASTM standard D 3171. The standard states different procedures for different tasks. When using acid digestion for measuring fiber volume fraction the “B” procedure is to be used. The standard states that one is to dissolve a sample weighing approximately 1g in 200 C° sulfuric acid for 3–4 hours. The dissolved matrix material is then oxidized via hydrogen peroxide. The fiber is then filtered, dried and weighed. (Cann, 2008)

2.2.2 Optical measuring

Although the most common method for measuring the fiber volume fraction is acid digestion, microscopy-based image analysis is also being used. A benefit of this method is that it can be used for microscopic level studying.

Microscopy based image analysis is mostly used when the aim is to get information of a highly localized part of the composite. To use photomicrographs for determining the fiber volume fraction of a composite, the fibers must be orientated perpendicularly to the image. If the composite consists of UD fibers, a single cross-sectional part of surface can be prepared and used for the image. However, if the composite has cross-ply orientated fibers, two or more images of the composite is required. For example, composite with fibers that are orientated in 0° and 90°, requires one image that is perpendicular to the ply that contains the fibers aligned in 0° and one that is perpendicular to the ply that contains the fibers in 90°. The microscope that is used for the images is typically set to magnifications between $100\ X$ and $2500\ X$. (Cann, 2008)

Once the images have been taken, the images are converted into a binary image (black-and-white) with a segmenting procedure. During this procedure a threshold for "gray level" is set to determine if a pixel will be white or black. Every pixel that has a higher gray level than the threshold will be black and every pixel that is lover will be white. This procedure is done to be able to separate between the fibers (white pixels) and matrix (black pixels). (Cann, 2008)

When the images have been converted into binary images, the fiber volume fraction can be obtained. There are two methods that can be used for this. The areal method and the fiber counting method. The areal method is done by calculating the number of black pixels and white pixels in a specified region of the image. Typically, a histogram that shows these numbers is made. Once this is done the fiber volume fraction can be calculated by simply dividing the number of black pixels with the total number of pixels. The fiber counting method requires a different type of binary image. The image is made such that the fibers appear as an isolated white region. The number of fibers is multiplied with the cross-sectional area of the fibers. This value is then divided with the total area in the specified area. (Cann, 2008)

2.3 **Unit-cell modelling**

Unit-cell modelling is a method that includes modelling unit-cells of a composite. The unit-cells are modelled with a 3D design software. From the models one can estimate the fiber volume fraction. The software provides the volume of the solid bodies in the design and the total volume of the unit-cell can be determined via the software´s measuring tool. Fig. 4 shows an image of a typical textile unit-cell. Modelling is a good method when dealing with textiles that are woven since the fiber volume can´t be analytically calculated. (Cann, 2008)

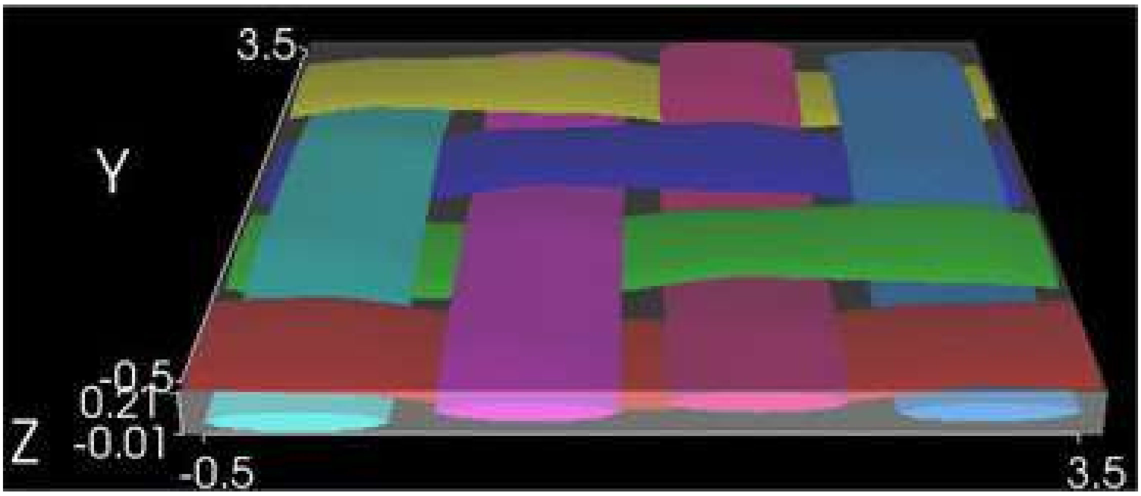

Figure 4. Unit-cell modelling (Cann, 2008)

2.4 **Fiber volume fraction via mass and volume**

The fiber volume fraction of a composite can be estimated if the mass and volume properties are known for the matrix material and textile. There are two alternatives for how the calculations are done. These alternatives can only be used for composites with uniform textile mass. This means that the textile mass is the same through the entire composite. (Velmurugan, 2012)

2.4.1 Alternative 1

To do the calculations for this alternative, the density of the textile, finished composite and matrix material must be known. The density of the yarn material is typically given by the manufacturer and the densities of the finished composite and matrix material can be measured. The step-by-step calculations and final equation (equation 6) can be seen below.

$$m_{tot} = m_1 + m_2 = \rho_{tot} V_{tot} = \rho_{fiber} V_{fiber} + \rho_{matrix} V_{matrix}$$

Since $f_i = \frac{V_i}{V_{tot}}$, V_{fiber} and V_{matrix} are written as $f_{fiber} V_{tot}$ and $f_{matrix} V_{tot}$.

$$\rho_{tot} V_{tot} = \rho_{fiber} f_{fiber} V_{tot} + \rho_{matrix} f_{matrix} V_{tot}$$
$$\rho_{tot} = f_{fiber} \rho_{fiber} + f_{matrix} \rho_{matrix}$$

Since $1 = f_1 + f_2$, f_{matrix} is written as $1 - f_{fiber}$.

$$\rho_{tot} = f_{fiber} \rho_{fiber} + \left(1 - f_{fiber}\right) \rho_{matrix}$$

$$\rho_{tot} = f \rho_{fiber} + (1 - f) \rho_{matrix}$$

$$\boldsymbol{f = \frac{\rho_{tot} - \rho_{matrix}}{\rho_{fiber} - \rho_{matrix}}} \tag{6}$$

(Velmurugan, 2012)

2.4.2 Alternative 2

To have alternative 2 as an option, a constant thickness is required for the composite. Alternative 2 is a method used when only the area mass of the textile material is known. The unit for area mass is most often $^{kg}/_{m^2}$. The step-by-step calculations and final equation (equation 7) can be seen below.

$$f = \frac{V_{textile}}{V_{tot}} \text{ and } 1 - f = \frac{V_{matrix}}{V_{tot}} = \frac{\frac{m_{matrix}}{\rho_{matrix}}}{A\, t_{tot}}$$

In the next step one replaces the mass of the matrix with the difference of the total mass and textile mass.

$$1 - f = \frac{m_{tot} - m_{textile}}{\rho_{matrix}\, A\, t_{tot}} \tag{7}$$

(Velmurugan, 2012)

3 METHOD

This chapter describes the methods used for analytical calculations, modelling and the microscopic images.

3.1 Analytical calculations

As mentioned the fiber volume fraction can be calculated analytically for some cases. Composites that include textiles with fibers that have circular yarn cross-sections and are placed straight are included in this category. For example, UD textiles with hexagonal stacking or square stacking and 0/90 textiles. 0/90 means that one layer of yarns is at an angle of 90° and the other at 0°. The calculations can be done if the cross-sectional radius and distance between the yarns is known. When analytically calculating the fiber volume fraction, it is assumed that each of the textile yarns lengths are equal. Thus, the length can in some cases be neglected. Yarn-spacing is expressed as *p*. This is a relation between the cross-sectional radius of the yarns (r) and the distance between them (a). This is demonstrated in Fig.5 and equation 8.

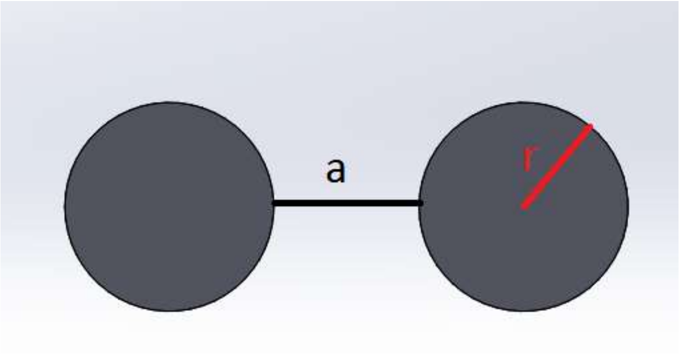

Figure 5. Schematic of yarn-spacing and radius

$$p = {}^{a}\!/_{r} \qquad (8)$$

3.1.1 UD hexagonal stacking

When calculating the fiber volume fraction analytically the first step is to calculate the total area of the triangle seen in fig.6. The second step is to calculate the area that the yarns cover within the triangle. Once these values are calculated, the last step is to divide the area of the yarns within the triangle with the total area of the triangle. The equation used for the calculations can be seen in equation 9 and results in fig. 7.

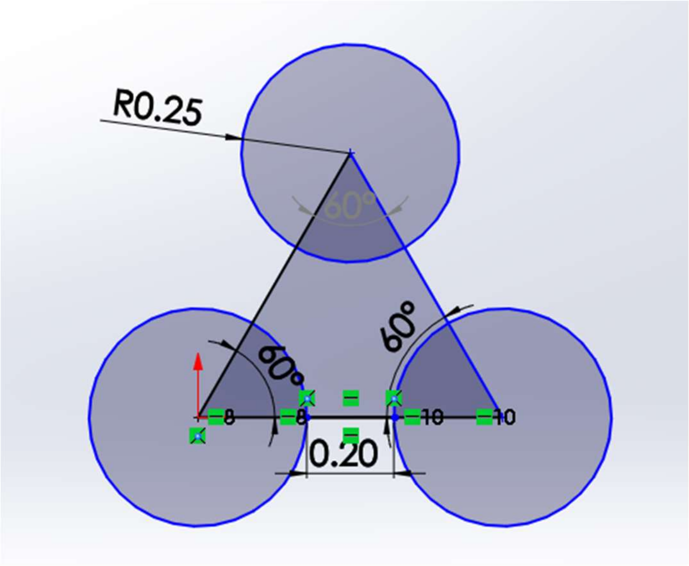

Figure 6. Area of interest for UD hexagonal stacking

$$f = \frac{V_f}{V_T} = \frac{A_f}{A_T}$$

$$A_f = \frac{\pi r^2}{2}$$

$$A_T = \frac{(a + 2r)^2 * \sin 60^\circ}{2}$$

$$f = \frac{\frac{\pi r^2}{2}}{\frac{(a + 2r)^2 * \sin 60^\circ}{2}} \quad , (a = pr), (\sin 60^\circ = \sqrt{3}/_2)$$

$$f(p) = \frac{\pi r^2}{(pr + 2r)^2 * \left(\sqrt{3}/_2\right)}$$

$$f(p) = \frac{\pi r^2}{r^2(p+2)^2 * \left(\sqrt{3}/_2\right)}$$

$$\boldsymbol{f(p)} = \frac{\boldsymbol{\pi}}{(\boldsymbol{p}+\mathbf{2})^2 * \left(\sqrt{\mathbf{3}}/_\mathbf{2}\right)} \tag{9}$$

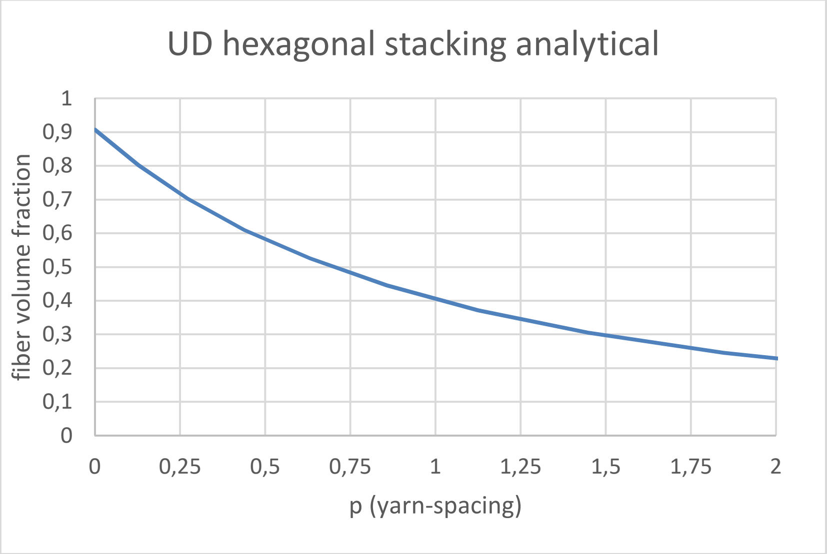

Figure 7. UD hexagonal stacking analytical

3.1.2 UD square stacking

When calculating the fiber volume fraction of a UD textile with square stacking, the procedure is similar to that of calculating the fiber volume fraction of a UD textile with hexagonal stacking. The difference is that the area of interest is a square. The equation used for the calculations is equation 10. Fig. 8 illustrates the area of interest and fig. 9 the results.

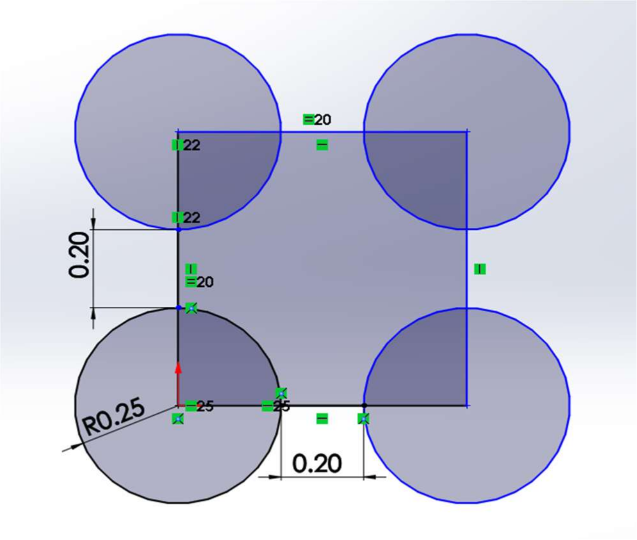

Figure 8. Area of interest for UD square stacking

$$f = \frac{V_f}{V_T} = \frac{A_f}{A_T}$$

$$A_f = \pi r^2$$

$$A_T = (2r + a)^2$$

$$f = \frac{\pi r^2}{(2r + a)^2}$$

$$f = \frac{\pi r^2}{(2r + a)^2} \qquad , \qquad (a = pr)$$

$$f(p) = \frac{\pi r^2}{(2r + pr)^2} = \frac{\pi r^2}{r^2 (2 + p)^2} = \boldsymbol{\frac{\pi}{(2 + p)^2}} \qquad (10)$$

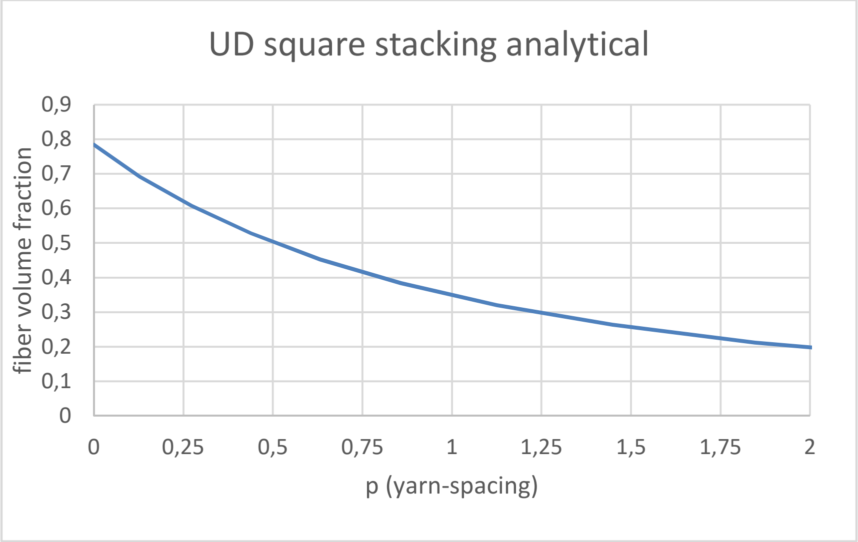

Figure 9. UD square stacking analytical

3.1.3 0/90 textile

For a textile with the yarns orientated 0° and 90° the calculations for analytical fiber volume fraction require the volume for the area of interest. The total volume is calculated by multiplying the cross-sectional area with the length. The fiber volume is calculated by multiplying the area of fiber within the area of interest with the length. Once these values are known, the fiber volume is divided by the total volume. Equation 11 illustrates the calculations. Fig. 10 illustrates the areas of interest and fig. 11 the results.

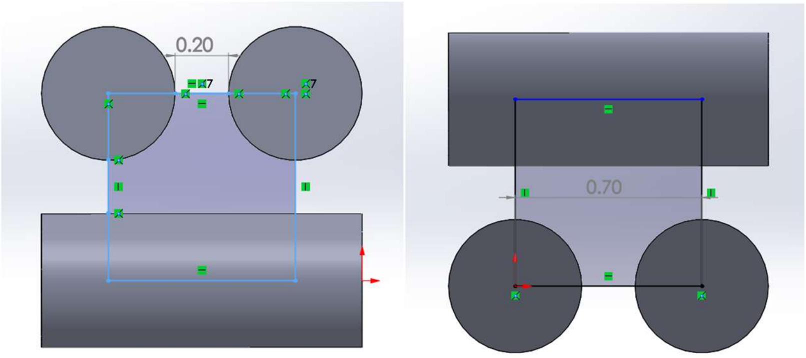

Figure 10. Front and side view for area of interest of a 0/90 textile

$$f = \frac{V_f}{V_T}$$

$$V_f = (2r + a)\frac{\pi r^2}{2} * 2$$

$$V_T = (2r + a)^3$$

$$f = \frac{(2r + a)\frac{\pi r^2}{2} * 2}{(2r + a)^3}$$

$$f = \frac{\pi r^2}{(2r + a)^2} \quad ,(a = pr)$$

$$f(p) = \frac{\pi r^2}{(2r + pr)^2} = \frac{\pi r^2}{r^2(2 + p)^2}$$

$$\boldsymbol{f(p) = \frac{\pi}{(2 + p)^2}} \tag{11}$$

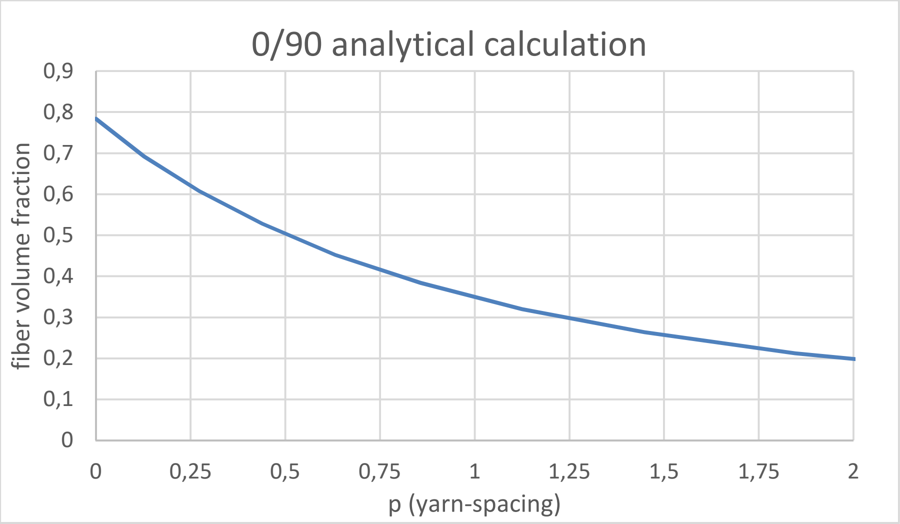

Figure 11. 0/90 analytical calculation

3.2 **3D Modelling**

The motivation for modelling is that the fiber volume fraction can´t be analytically estimated for most textiles. To estimate fiber volume fraction, the volume of fiber within the unit-cell must be known. To calculate the volume of fiber, the length of each yarn must be known (see equation 2). Since most textiles include yarns that are not straight, the length can´t be analytically calculated. The numeric method that is in some cases used is the elliptic integral of first kind (see equation 12). This method gives an estimate of the length. Fig. 12 illustrates yarn length and cross-section.

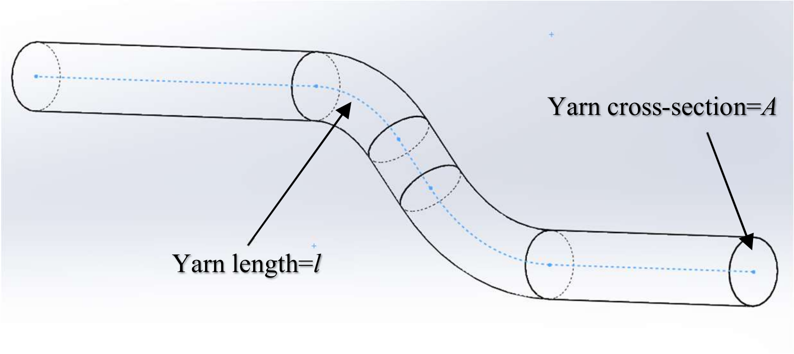

Figure 12. Schematic of yarn length and cross-section

$$V = A * l \tag{3}$$

$$F(\sin ø, k) = \int_{k}^{\sin ø} \frac{dt}{\sqrt{(1-t^2)(1-t^2k^2)}}, \qquad 0 \leq k^2 \ and \ \sin ø \leq 1 \tag{12}$$

The approach to this modelling task was to create models of textiles that are common in composite engineering. Such as plain weave, twill weave and satin weave. Models of textiles that can be analytically solved were included for comparison to analytical results. Numerous models for each type of weave was created, with different yarn-spacing and cross-sections. The models were done with a 3D design software called SolidWorks. They consist of three or more yarns. These yarns represent a unit-cell of a composite. It is assumed that the textiles structures repeat themselves systematically and that the thickness of the yarns is constant. The SolidWorks software was used to obtain the volume of fiber and the total volume in the unit-cell. By having these two values, one can anticipate the fiber volume fraction.

As already mentioned, the calculations are done for a single unit-cell. A unit-cell is a specific small portion of the composite that shows the structure of the yarns. Fig. 13 illustrates a unit-cell where the left side represents a unit-cell and the right side the entire textile.

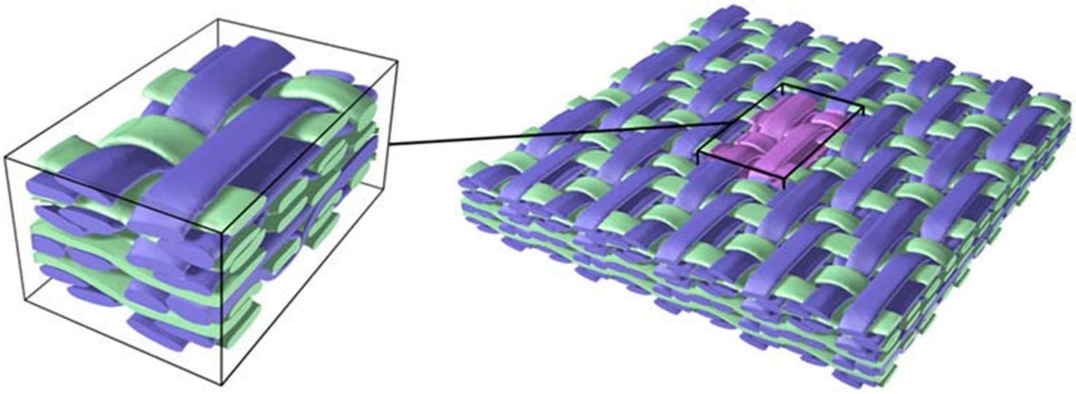

Figure 13. Unit-cell (Researchgate, u.d.)

The calculations for the fiber volume fraction were done by creating the unit-cell, calculating the volume of the unit-cell and obtaining the fiber volume via mass properties in SolidWorks. The unit-cell volume is calculated by multiplying the cross-sectional area of the unit-cell with its length. The cross-sectional area is obtained from the sketch that is required to perform the extruded cut that creates the unit-cell and the length by simply measuring it with the software. Once these values are known the fiber volume fraction can be calculated by dividing the fiber volume with the unit-cell volume. The procedure for changing the yarn-spacing was to change the cross-sectional radius of the yarns. Thus, affecting the yarn-spacing. Every modelling procedure was done with a yarn-spacing to radius relation changing from approximately zero to two (*p=0-2)*.

3.2.1 Cases that can be analytically calculated

The fiber volume fraction can be determined analytically for composites that contain only textiles with yarns that are straight and non-woven. Textiles that include yarns that are all placed in the same direction are called UD textiles. These textiles typically have hexagonal stacking of the yarns. Textiles that are non-woven and not UD, often include an expression for how the yarns are placed. For example, $[0/90]$ means that the first layer of the yarns is placed in 0° and the other layer at 90°. (Cann, 2008)

The aim with these models is to show that the results are the same for modelling and analytically calculating. To demonstrate how the yarn-spacing affects the fiber volume fraction for textiles that are non-woven and have straight yarns, UD models and $[0/90]$ models were created. To get a better understanding of the modelling process, see Fig.14 (yarn-spacing), Fig.15 (UD model) and Fig. 16 ($[0/90]$ unit-cell)

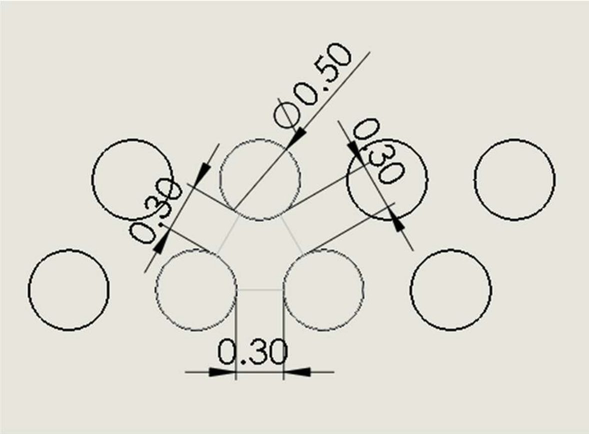

Figure 14. Yarn-spacing drawing

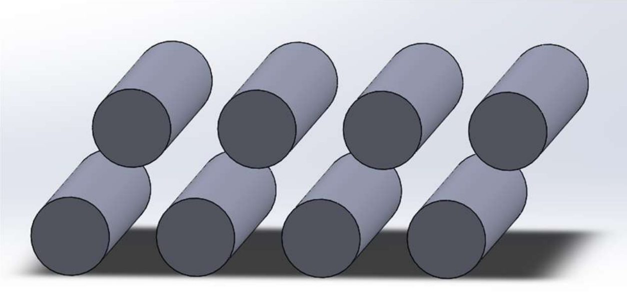

Figure 15. Isometric view of UD model

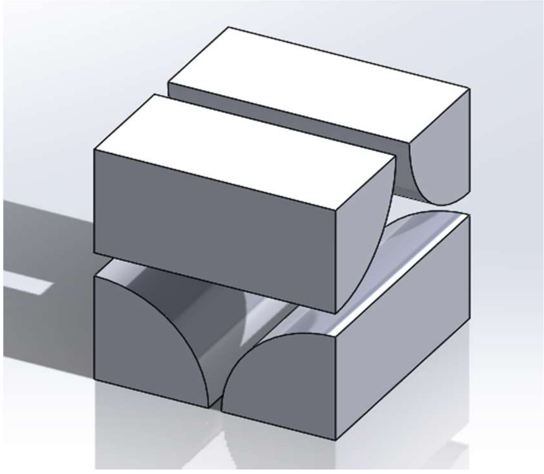

Figure 16. Isometric view of 0/90 unit-cell

3.2.2 Plain weave

A plain weave is a common and simple weave. In a plain weave the warp and weft yarns form a simple pattern. Warp yarns are yarns that are placed in the vertical direction and weft yarns are placed horizontally. Each weft yarn crosses a warp yarn by going over one and under the next. Plain weaves are commonly used in flat composites where drape is not required (ACP Composites, 2011). Fig. 17 shows the weave pattern of a plain weave textile, fig. 18 a model and fig. 19 a unit-cell.

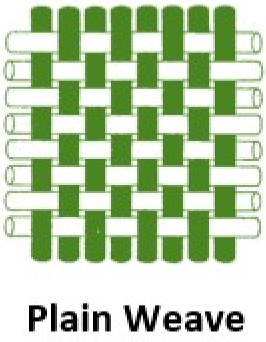

Figure 17. Plain weave (Sobuj, 2018)

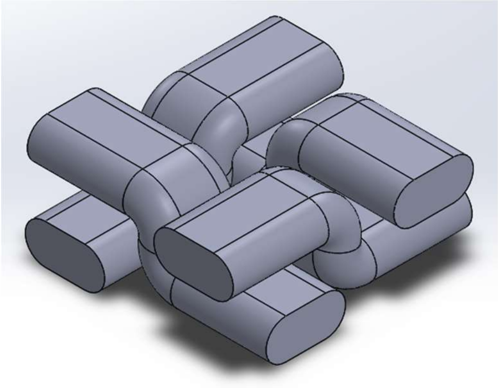

Figure 18. Plain weave model

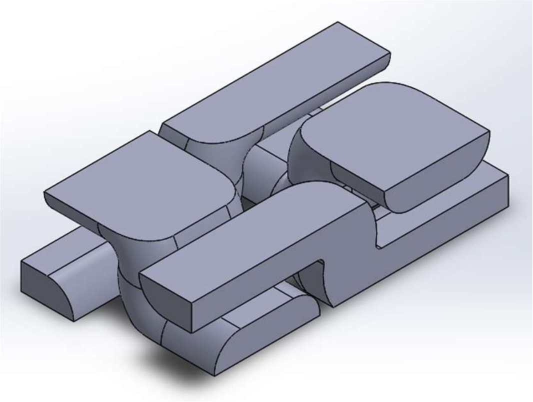

Figure 19. Plain weave unit cell

The plain weave models consist of 4 yarns. In this case the effect on fiber volume fraction for a plain weave was studied by creating numerous models for plain weaves with circular and elliptical yarn cross-section.

3.2.3 Twill weave

There are several types of twill weaves. A twill weave is done by passing the weft yarns under one or more warp yarns and then over one or more warp yarns. Twill weaves have a characteristic diagonal pattern which is created by each row having an offset as to where the interlacing of warp and weft yarn occurs compared to the previous row. (TextileSchool, 2018)

Twill weaves can be categorized as to being warp faced or weft faced and balanced or non-balanced. Warp faced means that the warp yarns are the ones passing over and under the weft yarns. Weft faced is the reverse, the weft yarns is responsible for passing over and under the warp yarns. Balanced twill weaves are weaves where each yarn passes over and under the same amount yarns. For example, a warp yarn passes under two weft yarns and then over two in a continuous pattern. Non-balanced twill weaves are the opposite, the over and under passes are not equal. For example, a warp yarn passes under once and then over twice. (TextileSchool, 2018)

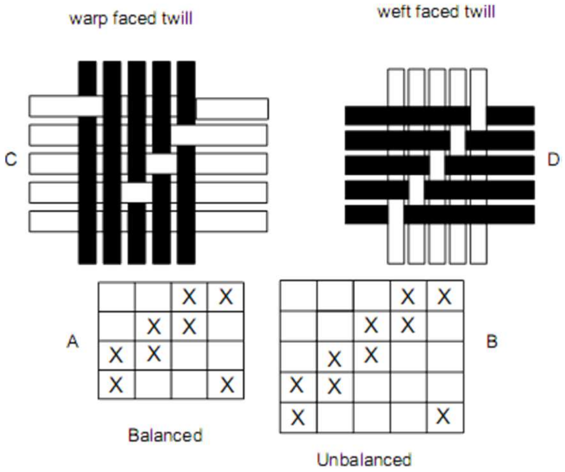

Figure 20. Warp- and weft faced/balanced and non-balanced (TextileSchool, 2018)

In Fig. 20, c and d illustrate the difference between warp faced and weft faced. A and b illustrate the difference between balanced and non-balanced. Each under pass is marked as an “X”.

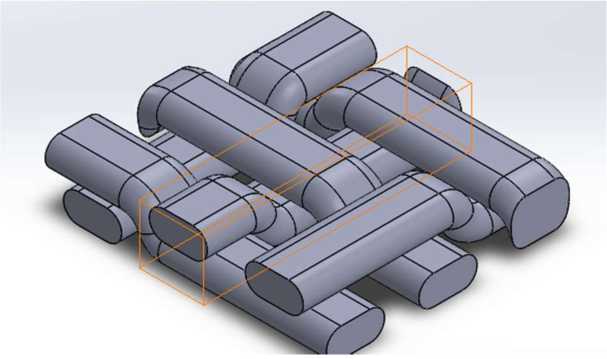

Figure 21. 2/2 twill weave model

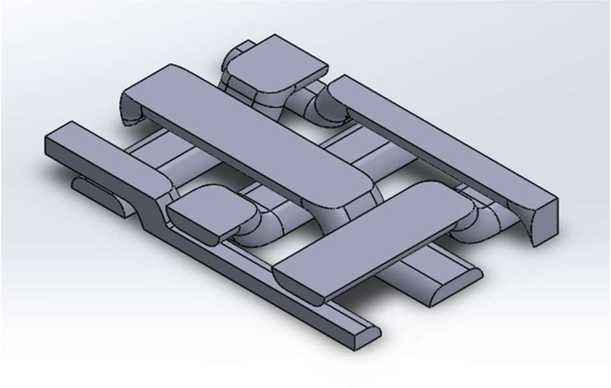

Figure 22. 2/2 twill weave unit-cell

Twill weaves can be expressed as *a/b*. Where *a* is the amount of under passes, and *b* the over passes. Two types of twill weaves were modelled. A 1/3 twill weave and a 2/2 twill weave. In this case the effect on fiber volume fraction for a twill weave was studied by creating numerous models for both weave types with an elliptical yarn cross-section.

3.2.4 Satin weave

Satin weaves are weaves where the weft yarn floats over more than three warp yarns or vice versa, before interlacing under one. The most common satin weaves are 4-harness, 5-harness and 8-harness weaves. Meaning that the number of over passes before a under pass is 3,4 and 7. (ACP Composites, 2011)

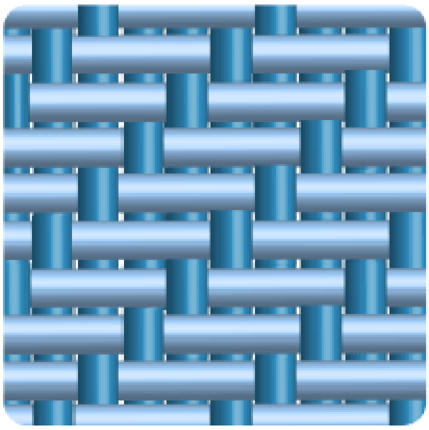

Figure 23. 4-Harness satin weave (ACP Composites, 2011)

To study the effect of yarn-spacing on a satin weave, a 4-harness, 5-harness and 8-harness satin weave was modelled. The modelling procedure was nearly identical to the 1/3 twill weave procedure. An image of the 5-harness model and unit-cell is present in figures 24 and 25. It is expected that the results will be similar since the number of under/over passes per unit cell is equal.

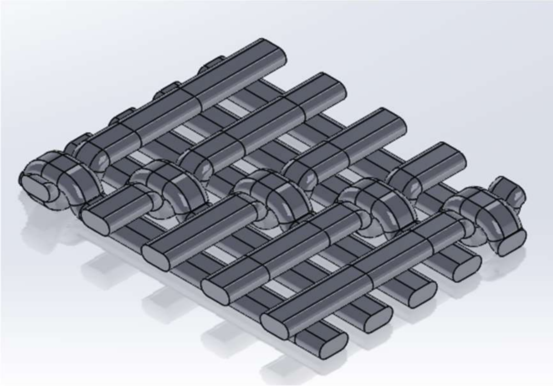

Figure 24. 5-harness satin weave model

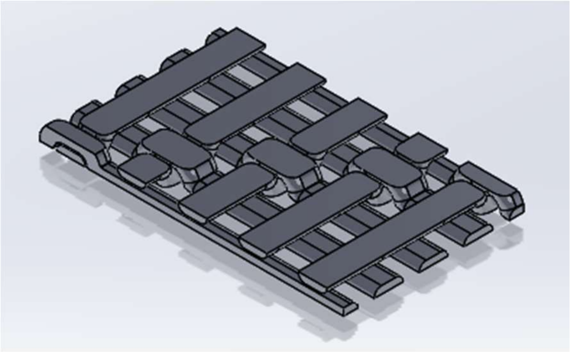

Figure 25. 5-harness satin weave unit-cell

3.3 **Microscopic images**

The procedure for the microscopic images was to polish the composite pieces and then photograph them under a microscope. The polishing was done with several sandpapers. Starting with a rough paper and finishing with an extremely smooth paper. The images were taken with reflected light. Carbon-fiber composite, glass-fiber composite and a bio-composite was photographed.

4 RESULTS

This chapter describes the results of analytical calculations, modelling and the microscopic images. It is structured by first discussing the analytical calculations. Proceeding with the modelled results and finishing with the microscopic images. All results are given with a yarn-spacing ranging from approximately 0-2.

4.1 Analytical calculations

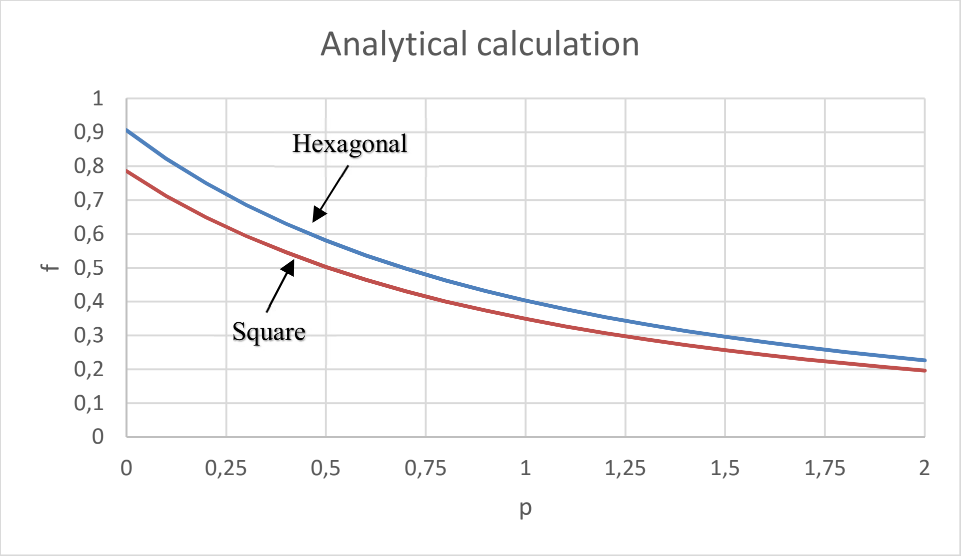

Figure 26. Analytical calculation results

Fig.26 illustrates the results for the effect on fiber volume fraction due to increase in yarn-spacing. The blue curve represents UD hexagonal stacking and the red represents UD square stacking. During the calculations, it became clear that the results are identical for UD square stacking and the 0/90 textile. Fig. 26 shows that increasing yarn-spacing decreases the difference in fiber volume fraction. Among the common textiles, UD textile with hexagonal stacking provides the highest fiber volume fraction. Thus, the blue curve server as a theoretic upper limit. With no yarn-spacing, this gives a value of 0,907 fiber volume fraction.

4.2 **3D Modelling**

This chapter discusses the modelling results. It is structured by first discussing the models of textiles that can be analytically calculated. Specifically, to show that the modelled results are the same as the analytical results. Thus, proving that modelling gives accurate results. The chapter then proceeds by going over different textile weaves. When calculating the fiber volume fraction, the value for spacing between the yarns is expressed in the same manner as for the analytical calculations. It is relative to the radius of the yarn cross-section and is expressed as *p,* the distance between yarns divided by the cross-sectional radius. For the models with elliptical yarn cross-sections, the radius used is the larger one. Fig. 27 illustrates this, where radius *a* is the radius used.

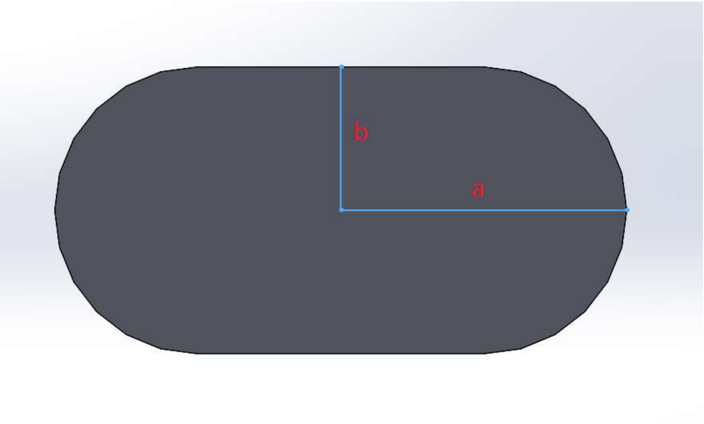

Figure 27. Elliptical cross-section radius

4.2.1 Cases that can be analytically calculated

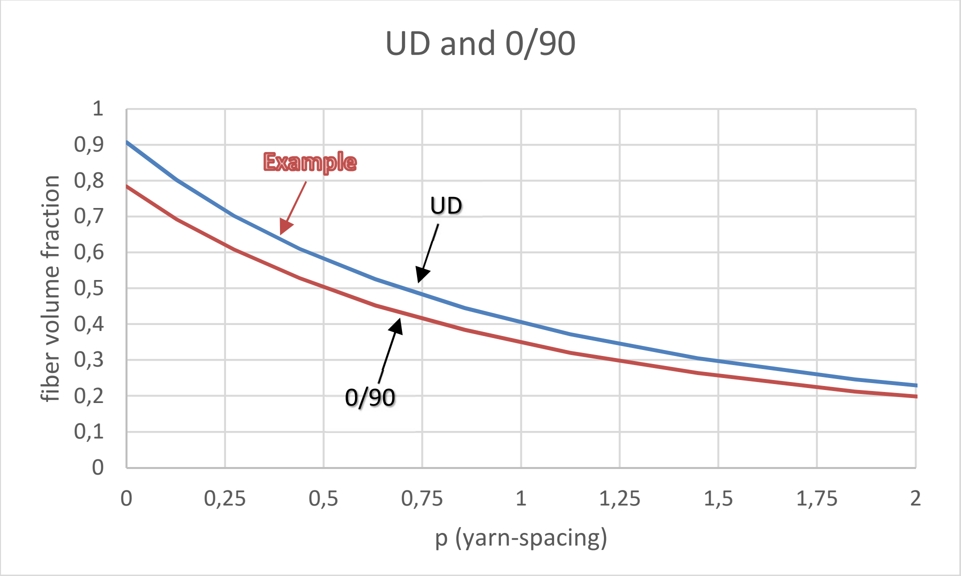

Figure 28. UD and 0/90 results

The graph in fig. 28 shows the decrease in fiber volume fraction due to increase in yarn-spacing. When comparing the results from analytical calculations and modelling of UD and [0/90], one can see that the results are identical. This is expected. It proves that the modelling method is accurate. The blue curve represents how fiber volume fraction changes for the UD model and the red curve for the [0/90] model. The x-axis represents yarn-spacing and the y-axis represents fiber volume fraction. As an example, at *p=0,5* the fiber volume fraction is approximately *0,59* for the UD model (see red arrow).

4.2.2 Plain weave

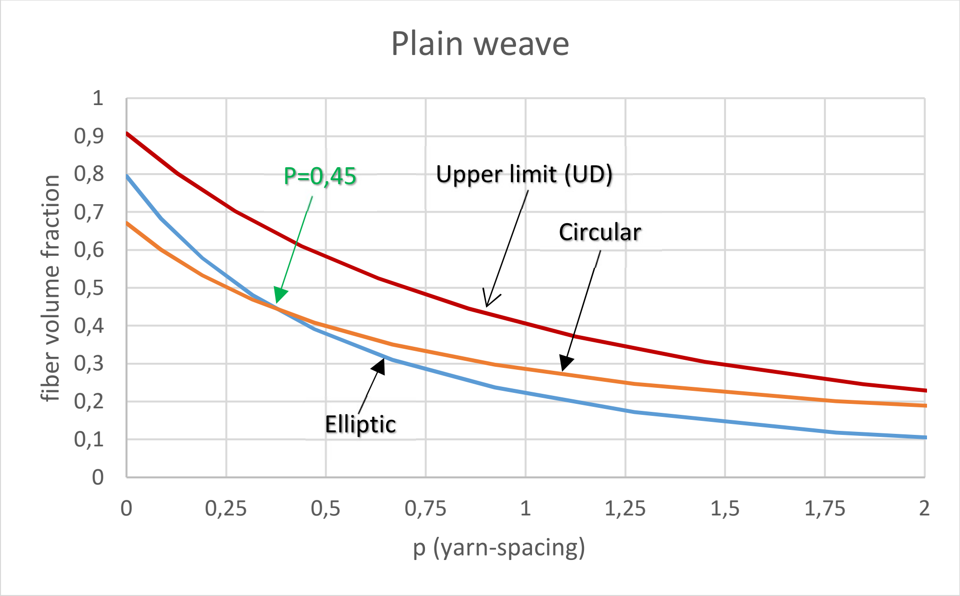

Figure 29. Plain weave results

Fig. 29 illustrates the effect yarn-spacing has on fiber volume fraction. The red curve represents an upper limit. The upper limit is the results obtained from the UD hexagonal stacked models. With no yarn-spacing, the elliptical shaped weave has a higher fiber volume fraction. At approximately p=0,45, the fiber volume fraction is equal, where after the circular weave has a higher fiber volume fraction.

4.2.3 Twill weave

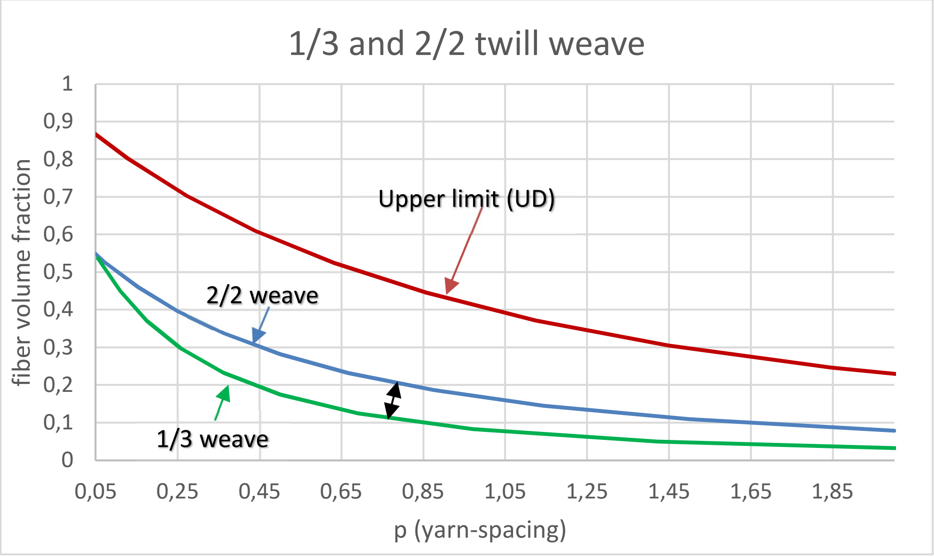

Figure 30. 1/3 and 2/2 twill weave results

Fig. 30 illustrates the effect on fiber volume fraction due to yarn-spacing. The blue curve represents the 2/2 weave and the green curve represents the 1/3 weave. It is clear that increasing yarn-spacing has a larger impact on fiber volume fraction for a 1/3 weave compared to a 2/2 weave. Fiber volume fraction is nearly identical at the lowest yarn-spacing value. The difference increases until approximately *p=0,75*. It then proceeds to decrease as the yarn-spacing increases.

4.2.4 Satin weave

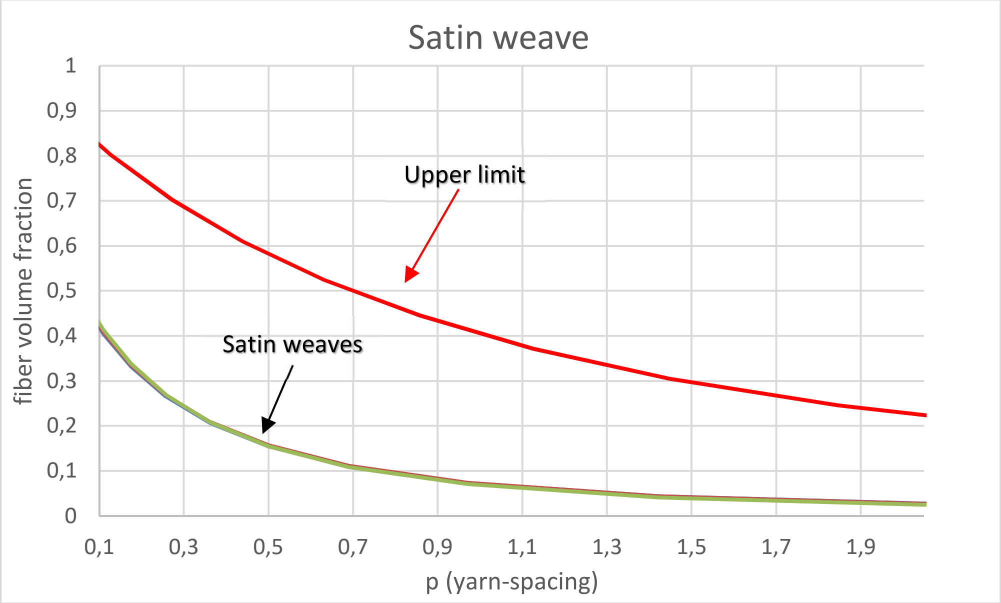

Figure 31. Satin weave results

As expected, the results are nearly identical. Fig. 31 shows the results for all three weaves. The results are so similar that it is difficult to differentiate between the three curves. It is likely that the slight variance is due to modelling differences that are non-related to yarn-spacing.

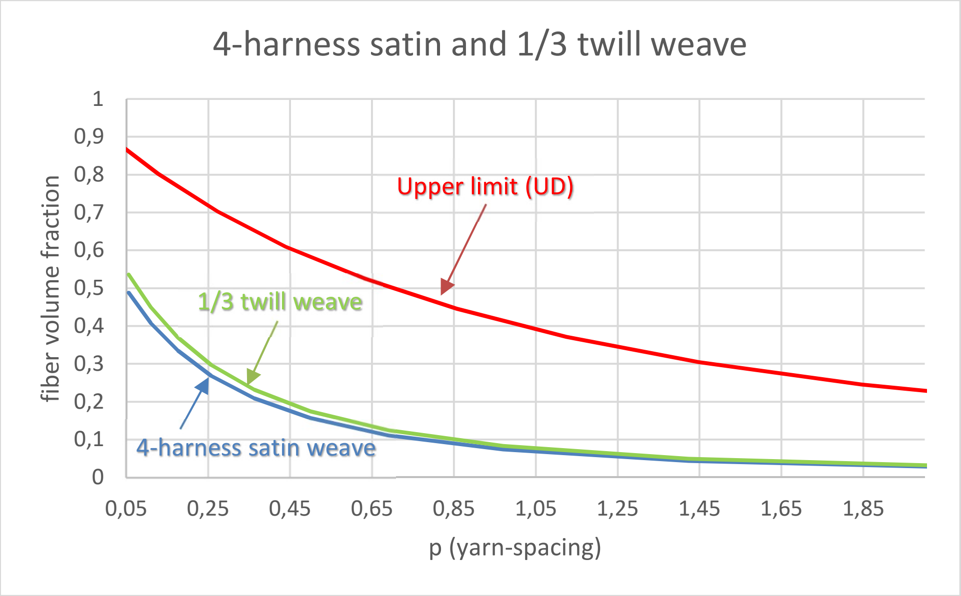

Figure 32. 4-harness satin and 1/3 twill weave results

Fig. 32 illustrates the 4-harness satin weave results compared to a 1/3 twill weave. The green curve represents the results obtained from the 1/3 twill weave, while the blue curve represents the results from the 4-harness satin weave. The results are extremely similar. Increasing the yarn spacing decreases the difference in fiber volume fraction. After *p=1,05* the fiber volume fraction is nearly identical.

4.3 **Microscopic images**

This part discusses actual fiber-reinforced composites. A few composite test pieces were polished and photographed under a microscope to study how the textiles are structured inside the composite. This part includes a discussion of weave pattern, stacking, microscopic vs macroscopic and yarn cross-section.

4.3.1 Weave pattern

Figure 33. Twill weave microscopic image (side view)

Figure 34. Plain weave microscopic image (top view)

Fig. 33 illustrates 2/2 twill weave pattern from a side view and fig. 34 a plain weave from a top view. This shows that the weave pattern is the same as for the modelled textiles. However, from fig. 33 it is also clear that properties such as yarn-spacing and yarn cross-section is not constant as they are in the models.

4.3.2 Stacking

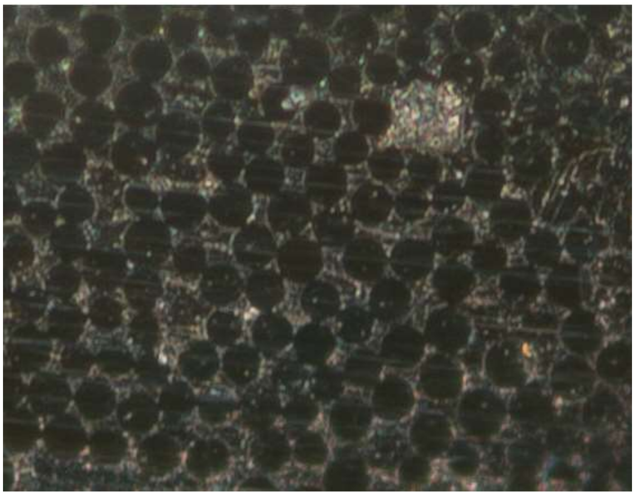

Figure 35. Microscopic filament stacking image

Fig. 35 illustrates filament stacking. Filament stacking is often described as being hexagonal or square. The image shows that in practice, the stacking is unlikely to be constant. The black circular objects are the filament. When analyzing the image, it appears that both hexagonal and square stacking is present.

4.3.3 Macroscopic vs microscopic

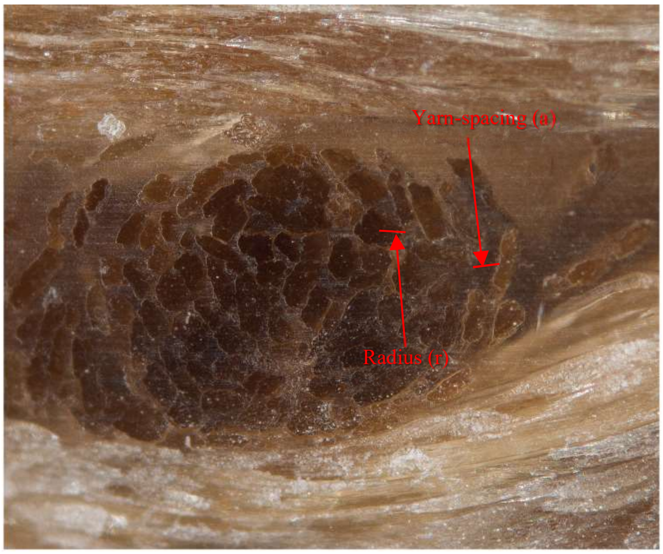

Figure 36. Example of microscopic study area

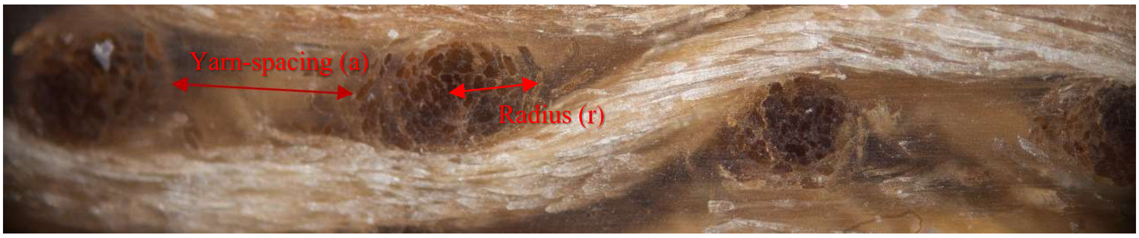

Figure 37. Example of macroscopic study area

As already mentioned, fiber volume fraction can be studied at a microscopic and macroscopic level. Figures 36 and 37 illustrate the difference in study area for microscopic and macroscopic fiber volume fraction. Fig. 36 is an example for a microscopic level and fig. 37 for a macroscopic level.

4.3.4 Yarn cross-section

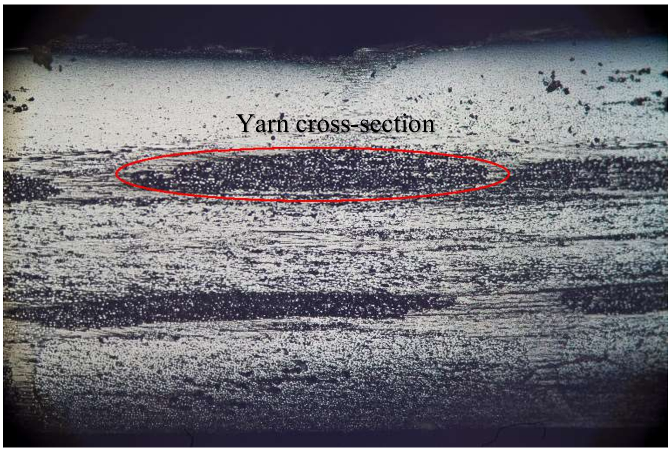

Figure 38. Microscopic image of yarn cross-section (1)

Figure 39. Microscopic image of yarn cross-section (2)

Fig. 38 and 39 illustrate how a typical yarn cross-section looks in practice. These images show that they have an elliptic form. It is also clear that every yarn is different, not constant. In fig. 38, the black elliptic parts are yarn cross-sections. In fig. 39 they are brown and elliptic.

5 DISCUSSION

The results obtained from this study are beneficial when choosing a textile for reinforcing properties of a composite. The charts give an accurate description of how yarn-spacing affects fiber volume fraction. However, the microscopic images show that the filaments in the yarn are unpredictable and not constant. Thus, the results can only be used as estimations.

Modelling textile unit-cells with SolidWorks serves as a useful tool with certain downfalls. Since the models rely on length and thickness etc. being constant, the results obtained can only be determined as estimations or averages.

6 CONCLUSION

When analyzing the results from modelling, it seems that one major factor for how much the fiber volume fraction decreases when increasing yarn-spacing is the number of interlacements between the yarns. From the results, one can determine that more interlacements lead to a higher fiber volume fraction. This is most likely a result of the increase in packing from the interlacing of yarns. The results for the 1/3 twill weave and all satin weaves are nearly identical and they all have one interlacement per unit-cell. Whereas the results from plain weave and 2/2 twill weave show that fiber volume fraction is higher. It is also apparent that the form of yarn cross-section has a significant impact. From the plain weave results, one can determine that at a low yarn-spacing, an elliptically shaped cross-section gives a higher fiber volume fraction. However, increasing yarn-spacing has a larger impact on an elliptical cross-section which leads to that the circular cross-section will have a larger fiber volume fraction when yarn-spacing is high.

Yarn-spacing (p)	0/90 (% of upper limit)	Plain circular	Plain elliptic	2/2 twill	1/3 twill and satin
0	86%	74%	86%	66%	63%
0,25	86%	70%	74%	54%	38%
0,5	88%	69%	66%	48%	28%
0,75	88%	71%	58%	46%	21%
1	85%	71%	56%	41%	19%
1,25	86%	71%	51%	40%	17%
1,5	87%	76%	50%	36%	13%

Table 1. Results compared to upper limit

Table 1 illustrates the modelled results compared to the UD hexagonal stacked results. As mentioned, the UD hexagonal stacked results serve as an upper limit for fiber volume fraction. The first column represents yarn-spacing, the other columns represent fiber volume fraction as a percentage of the upper limit at that specific yarn-spacing. For example, at a yarn-spacing of 0,25 the 2/2 twill weave has a fiber volume fraction that is 54 % of the upper limit at that specific yarn-spacing. The values in table 1 are approximations.

To determine if this modelling method is a reliable method. One could say that it is a suitable method when analyzing the effect, a certain factor has on fiber volume fraction. However, since it is nearly impossible to model a textile precisely as it would be in practice, it is not a reliable method to determine fiber volume fraction for any specific composite prior to manufacturing. This is due to the variance in shapes of yarn cross-section, weave pattern and filament stacking etc. Which is apparent in the images taken with a microscope. The images show that practically none of these factors are constant in a composite.

7 SAMMANFATTNING

Syftet med detta arbete är att studera effekten trådavstånd har på fiber volymandel. Fiber volymandel är mängden fiber i en komposit. Fibern i en komposit läggs till i form av en textil. En textil uppgörs av trådar och trådarna av filament. Arbetet är relevant för komposit planering pga. ”the rule of mixtures”. ”The rule of mixtures” används för att estimera kompositers egenskaper, t.ex. elasticitetsmodul. Vid användning av ”the rule of mixtures”, krävs fiber volymandelen. Arbetet förvekligades genom att modellera textiler som används i kompositer. Modelleringen gjordes med programmet SolidWorks som är ett 3D planerings program. Motiveringen för modellering är följande. För att kunna estimera fiber volymandel av en komposit måste volymen av fiber räknas. Volymen kan inte räknas analytiskt för de flesta textiler eftersom längden för trådarna inte kan räknas analytiskt om tråden inte är rak. Eftersom SolidWorks inte vanligtvis används för denna sorts arbete, fungerar detta också som en studie för hur pålitlig metoden är.

7.1 Metod

Metoden för modellering var att skapa 3D modeller av textiler vars volym kan räknas analytiskt, plain weave textil, twill weave textil och satin weave textil. Dessa modeller användes för att estimera fiber volymandelen. Modelleringen gjordes genom att skapa en enhetscell av varje sorts textil. En enhetscell är en bit av textilen som beskriver textilens struktur i den minsta möjliga storleken. Med dessa enhetsceller räknades fiber volymandelen genom att dividera fiber volymen i enhetscellen med totala volymen av enhetscellen. För att få en bättre bild av modellerings metoden, se fig. 18 som beskriver modellen av plain weave och fig. 19 som beskriver enhetscellen för plain weave.

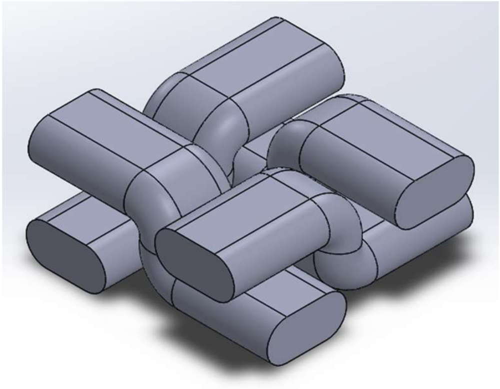

Figure 40. Plain weave model

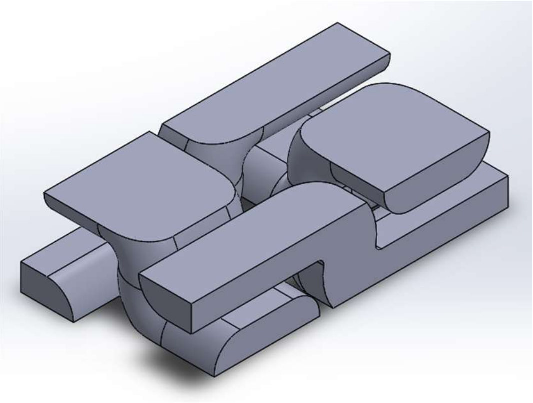

Figure 41. Plain weave unit-cell

Trådavståndets påverkan på fiber volymandel studerades genom att göra flera modeller för varje textil som har olika trådavstånd. Variation av trådavstånd förverkligades genom att minska på trådens tvärsnittliga area.

7.2 **Resultat och slutsats**

Vid analysering av resultaten gjordes en väsentlig observation. Det verkar som att för varje sammanflätning mellan trådar, ökar fibervolym andelen. Alla resultat presenteras med ett trådavstånds variation från 0 till 2. Trådavståndet ges som en relation mellan trådens tvärsnittliga radie och avståndet mellan trådarna. Se fig. 5 och ekvation 8.

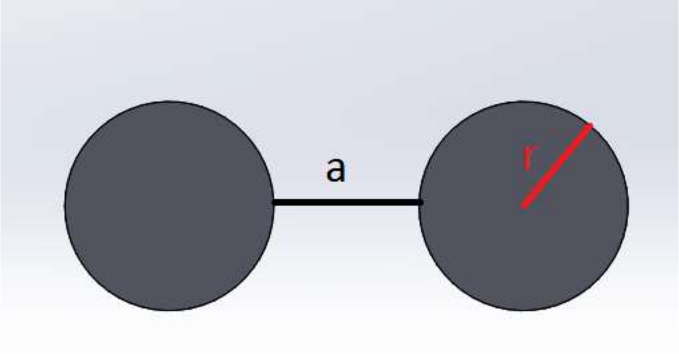

Figure 42. Schematic of yarn-spacing and radius

$$p = {}^{a}/_{r} \quad (8)$$

Fig. 29, 30 och 31 beskriver resultaten i jämförelse med en övre gräns. Övre gränsen är resultaten av UD textil med hexagonal packning av trådarna. Detta eftersom UD textil med hexagonal packning av trådarna ger den högsta packningen.

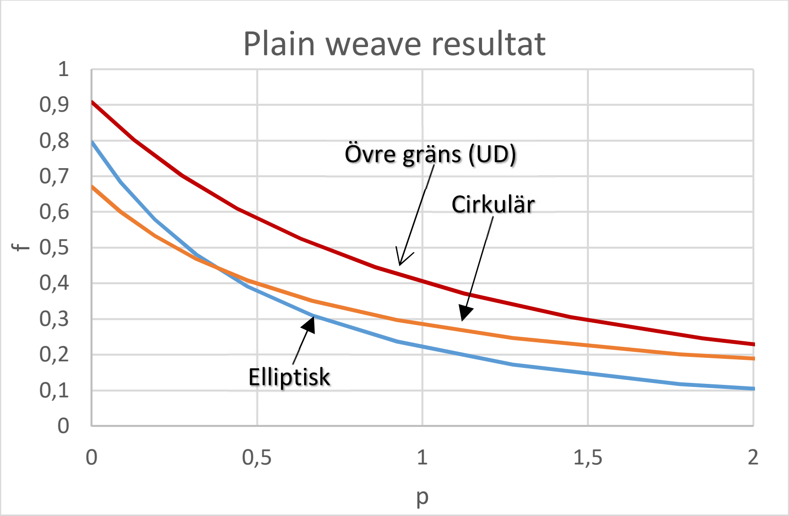

Figure 43. Plain weave results

För plain weave gjordes modeller med cirkulär och elliptisk tråd-tvärsnitt för studerandet av hur tvärsnitt av tråden påverkar fiber volymandelen vid ökning av trådavstånd.

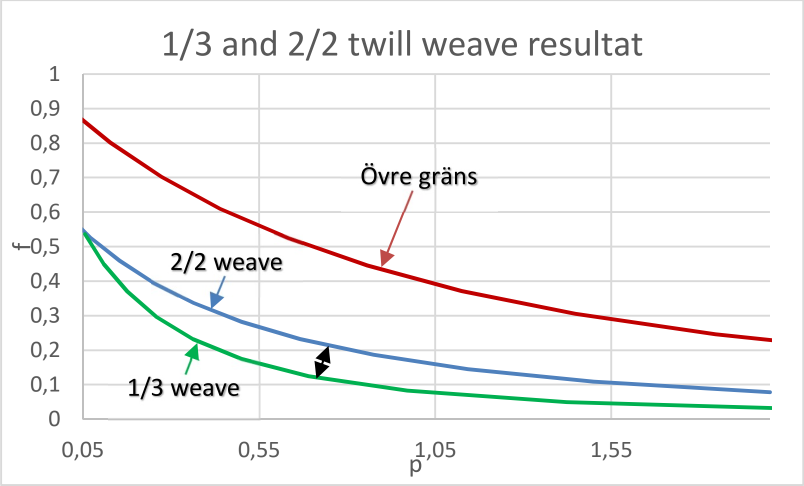

Figure 44. 1/3 and 2/2 twill weave results

För twill weave gjordes modeller för en 2/2 och 1/3 weave. Fig. 30 illustrerar resultaten för twill weave modellerna. Vid analysering av resultaten ser man att vid lågt trådavstånd är fiber volymandelen lika. Sedan ökar skillnaden till ungefär p=0,75 var efter skillnaden börjar minska.

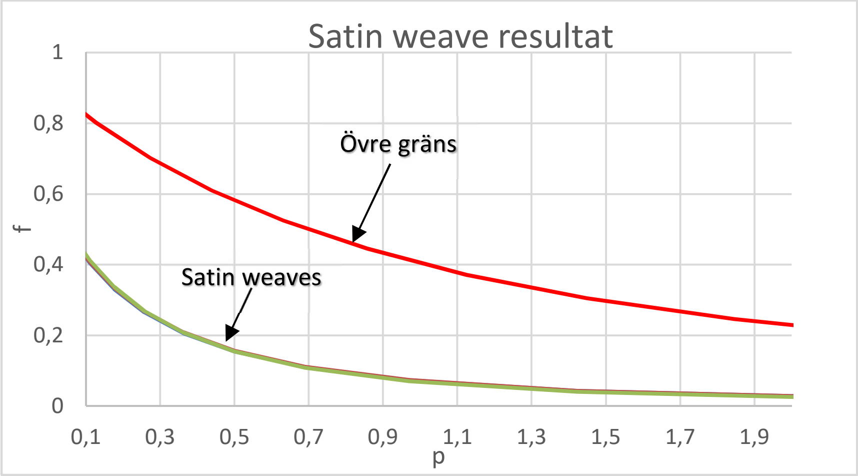

Figure 45. Satin weave results

För satin weave gjordes 3 olika modeller. En 4-harness, 5-harness och 8-harness satin weave. Fig. 31 illustrerar resultaten. Vid analysering av resultaten ser man att trådavståndets påverkan på fiber volymandel är nästan exakt lika. Resultaten är så lik varandra att det är svårt att skilja från varandra av grafen.

Figure 46. Twill weave microscopic image (side view)

Fig. 33 är en av de mikroskopiska bilderna som togs för att studera hur praktiska textiler är i jämförelse med modellerna. Vid analysering av fig. 33 ser man att egenskaper som trådavstånd och tvärsnitt varierar och är inte konstanta. I modellerna är dessa egenskaper konstanta.

Vid analysering av alla resultaten gjordes en väsentlig observation. Det verkar som att för varje sammanflätning mellan trådar, ökar fibervolym andelen. Mikroskopiska bilderna togs och analyserades för att studera hur lika/olika modellerade textilerna är i jämförelse med praktiska textiler. Det visade sig att i praktiken är textiler i kompositer väldigt oförutsägbara. Egenskaper som trådtjocklek, trådtvärsnitt osv. är aldrig konstanta. Slutsatsen av detta är att modellerings metoden som använts i detta arbete är bra för att studera effekten någonting har på fibervolym andel, men inte en optimal metod för estimering av fibervolym andel för en specifik komposit före produktion.

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