

CHALMERS



Modelling of Spread Tow Carbon Fabric Composites for Advanced Lightweight Products

Master's thesis in Applied Mechanics

EMINA MUSIC

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Department of Applied Mechanics

Division of Material and Computational Mechanics

CHALMERS UNIVERSITY OF TECHNOLOGY

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ABSTRACT

This master thesis covers evaluations of existing methodologies and the development of new ones for characterising mechanical properties of a spread tow carbon fabric composite. The project starts at a micro level, describing the constituents of the composite fabric and the interaction between them. A macro-level simulation is performed on a product, manufactured with the material in question, and the mechanical properties of the part are calculated.

It is important for the accuracy of the simulations to know the dimensions of the modelled fabric. Therefore measurements are performed on the fabric, to gain as real estimation of them as possible, rather than using the nominal values provided by the manufacturer. The measured dimensions proved that the fabric is not fully balanced and closely packed as desired, which influences the mechanical properties of the fabric.

The material properties obtained from several approximation methods are compared to experimental test data to validate the accuracy of the simulations. With the modelling methods adopted in the current work, slightly higher stiffness properties are obtained compared to the ones from the experimental tests. The main reason for this is most likely that the material in the simulation contains no imperfections, i.e. no defects are accounted for.

The most promising method at the present time is the WiseTex/TexComp method. With its analytical approach and detailed material parameters, properties of a composite material can quickly be evaluated. Using ABAQUS CAE and FEM simulation to predict the material properties works well for simple materials and geometries, but for more complex models, as in this study, inadequate results are obtained.

The analytical models are far from complete and show potential for further development. Since not all possible effects, i.e. environmental influence and defects in the inner structure of the fabric, have been included in the thesis.

Keywords: Composite modelling, TeXtreme, spread tow carbon fibre, RVE, WiseTex, Young's modulus

PREFACE

This Master's Thesis is for the degree Master of Science in Applied Mechanics at Chalmers University of Technology. The report covers analytical and numerical analysis of a spread tow carbon fibre composite. The work has been performed during 20 weeks at FS Dynamics in Gothenburg in cooperation with OXEON. FS Dynamics is a consultancy company for technical calculations and OXEON a manufacturer of carbon fibre fabrics.

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NOMENCLATURE

Roman letters

E	Stiffness (Young's) modulus [MPa]
G	Shear modulus [MPa]
L	Length [mm]
A	Area [mm^2]
F	Force [N]
d	Width [mm]
t	Thickness [mm]
N	Force per length [$\frac{N}{mm}$]
M	Moment per length [N]

Greek letters

ϵ	Strain $[-]$
σ	Stress [MPa]

Subscript

c	Composite
cs	Cross-section
f	Fibre
m	Matrix
S	Strand
L	Longitudinal
T	Transverse
LT	In-plane
d	Default
p	Ply

Abbreviations

$[ABD]$	Constituent matrix
$[A]$	Extensional stiffness matrix
$[B]$	Coupling stiffness matrix
$[D]$	Bending stiffness matrix

DICTIONARY

Bundle

A large amount of filaments (1.000 - 350.000) packed together, untwisted or twisted

Constituents

The components in a composite material

Continuous fibre

Long fibre

Discontinuous fibre

Short fibre, eg. chopped fibres, milled fibres or whiskers

Filament

Continuous fibre with approximately a diameter of 5-10 μm

Lamina

One layer of a unidirectional or bidirectional fabric

Laminate

A stack of lamina (plies) oriented in a specific manner to achieve desired material properties

Macro scale

Order of magnitude that is observable by the naked eye

Matrix

The component in the composite that binds the reinforcement

Meso scale

The scale between micro and macro. Approximately the size of an RVE

Micro scale

The scale of one fibre to some fibres diameter

Ply

See Lamina

Reinforcement

The component in the composite that gives the material its desired properties

RVE

A small section of the material, which contains all necessary information of the microstructure

Stack-up

The stack-up sequence refers to the amount of layers and their fibre orientation

Strand

Dry yarn which has been impregnated with matrix

Tape

A spread bundle

Tow

An untwisted bundle of continuous filaments

Unit cell

The composite material can be divided into repeating unit cells. The RVE is not necessarily a unit cell and vice versa

Warp

The yarns in a weave aligned with the direction going through the weaving machine

Weft

The yarns in a weave put crosswise (perpendicular) to the direction going through the weaving machine

Yarn

A bundle containing thousands of filaments

CONTENTS

1	Introduction	1
1.1	Background	1
1.2	Purpose	1
1.3	Scope	1
2	Theory	2
2.1	Composite components	2
2.1.1	Fibre	2
2.1.2	Matrix	2
2.2	Composite fabrics	3
2.2.1	Textile composites	3
2.2.2	Stack-up	4
2.2.3	Crimp	4
2.3	TeXtreme Spread Tow fabrics	5
2.4	Manufacturing methods for composite parts	6
2.5	Calculating methods for mechanical properties	7
2.5.1	Impregnated yarn (strand) properties	7
2.5.2	Main engineering constants	8
2.5.3	Constitutive characterisation matrix	9
2.5.4	Karkkainen approach	9
2.6	Homogenisation of the composite material	11
3	Method	12
3.1	Measuring of TeXtreme material dimensions	12
3.1.1	Thickness measurement	12
3.1.2	Yarn width and spacing measurement	13
3.2	Software usage	15
3.2.1	WiseTex family	15
3.2.2	TexGen	16
3.2.3	ABAQUS CAE	16
3.3	Chosen software path	19
4	Application	21
4.1	Background	21
4.2	Aim and limitation	21
4.3	Requirements for the shaft	21
4.3.1	Shafts made out of TeXtreme material	22
4.4	Simulation	22
4.4.1	Assumptions and Simplifications	22
4.4.2	The model	23
4.4.3	Method to evaluate results	24
5	Results and Discussion	25
5.1	Measuring results	25
5.2	Strand properties and engineering constants	25
5.3	Software usage	26
5.3.1	WiseTex	27
5.4	TexGen	28
5.5	ABAQUS CAE	28
5.5.1	Simple box	28
5.5.2	Unidirectional composite	29
5.5.3	TeXtreme model	29
5.6	Floorball shaft	29

6	Conclusions	31
7	Future work	32
	References	33
A	Floorball shaft	35
B	Confidential Experimental test of TeXtreme floorball shafts	36
C	Confidential SICOMP experimental test data	37
D	Confidential TeXtreme	38
E	WiseTex-ABAQUS	39

1 Introduction

This chapter covers the background, the purpose and the scope of the performed thesis work.

1.1 Background

The usage of composite materials is growing fast in areas such as aerospace, racing, sports, automotive and industrial products – all having extreme demands on material performance. In applications where stiffness, strength, low weight, and outstanding fatigue characteristics are critical requirements, carbon fibre composites may be a good choice due to their very high strength-to-weight ratio [1]. Oxeon AB develops, produces and markets patented Spread tow carbon reinforcements. The carbon fabric was launched as TeXtreme Spread Tow Fabrics in 2004. With TeXtreme superior surface smoothness, significant weight savings, improved mechanical properties and new design possibilities can be achieved.

A currently running nationally funded project lead by OXEON is aiming at characterising the mechanical properties of the TeXtreme material experimentally. The test programme is time consuming and very expensive, so the question of being able to predict the mechanical properties of the TeXtreme material through numerical simulation is very interesting, both from a design point-of-view but also from a cost perspective. The current Master thesis project is therefore focusing on evaluating the challenges in numerical modelling the TeXtreme material. The simulations are performed using the software programs WiseTex, TexGen, ABAQUS and MATLAB, and the results obtained are compared to existing experimental test data.

1.2 Purpose

The purpose of this project has been to develop and evaluate a methodology for characterising mechanical properties of TeXtreme using multi-scale modelling. Further, TeXtreme material properties, provided from experimental data, have been used for modelling the stiffness properties of a typical product, in this case a floorball shaft made of TeXtreme.

1.3 Scope

The goals set for this thesis work are:

1. Model the TeXtreme material on micro-, meso- and macro scale.
2. Evaluate the accuracy of the simulations compared to the results from the experimental test data.
3. Find the limitations of the used software programs.
4. Develop a simplified approach for determining the material properties.

For this, linear elastic¹ material models are assumed and effects like non-perfect material and environmental effects are not taken into account or evaluated. The main attention lies on the TeXtreme stiffness properties, while the strength is not considered.

¹No non-linear elastic material data is available.

2 Theory

In this chapter, the fundamentals of composite theory are presented. Starting with a presentation of the components in a composite, the various composite fabrics and the TeXtreme fabrics. The commonly used manufacturing methods for composite parts, are also briefly presented. Finally, the equations applied for calculating the composite properties and the homogenisation techniques used in the composite software WiseTex, are introduced.

2.1 Composite components

A composite material consists of at least two materials, where one act as binder (matrix) and the other as reinforcement. Unlike, e.g. alloys, the constituents² remain separate and are easily distinguishable [2], making the material heterogeneous [3]. It is the reinforcement which gives the composite its desired properties, whilst the matrix binds the reinforcement, holds them in place, transfers the load between the reinforcements [2] and protects the reinforcement from the environment [4]. Thus, the overall properties of a composite part depend on the properties of both components, the interface between them and the methods used to manufacture it.

2.1.1 Fibre

Composite materials can contain *particulate* (e.g. gravel in concrete), *discontinuous* and *continuous* fibre, see Figure 2.1. When using short (particulate or discontinuous) fibres the matrix must transfer the load between the reinforcement more frequently, resulting in a material with low composite properties, compared to the composites reinforced with continuous (long) fibres [2]. Glass fibres and Kevlar³ are widely used reinforcement constituents in composites and have both their advantages and disadvantages compared to carbon fibres. Glass fibres for example are cheaper but not as stiff as carbon fibres [6], whilst Kevlar has high tensile stress but poor compressive strength and is rather expensive [7].

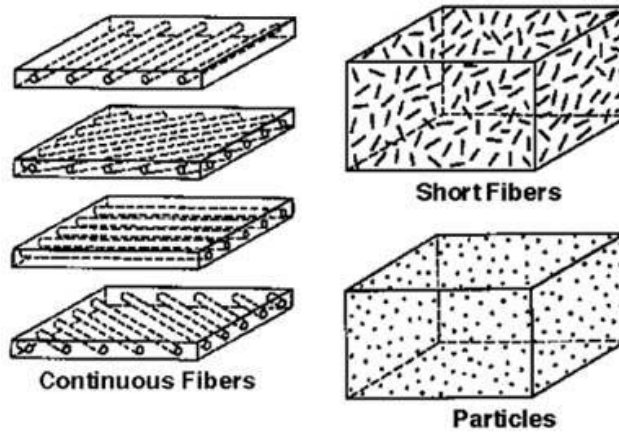


Figure 2.1: Illustration of the three different reinforcement types; Continuous fibre, discontinuous (short) fibre and particles [8].

2.1.2 Matrix

The binding constituents, the matrices, can be polymer, metal or ceramic, where polymer matrices are the most common. The two most commonly used polymeric materials are epoxy resins and polyester resins [2]. Composite properties are most efficient (largest load carrying properties) in the fibre direction, whilst the matrix properties dominate in the transverse direction to the fibres, as load must be transferred by the matrix between every fibre. [2]

²The components in a composite material are also referred to as constituents.

³Combination of para-phenylenediamine and terephthaloyl chloride [5].

2.2 Composite fabrics

When studying a composite material there are a lot of quantities to dissociate, for instance the difference between yarn and strand. Even though the fibres in a yarn are packed very close together into bundles, the fibre fraction can not be assumed to 100%, due to air gaps. Thus it may be useful to distinguish a bundle of dry fibre filaments, a “yarn”, and an impregnated yarn, a “strand”. The volume fraction fibre in strands can be calculated using the cross section area of the strand, A_{cs} , the cross section area of one filament, a_{cs} , and the amount of fibres in the tow, N

$$V_{f,s} = \frac{a_{cs}N}{A_{cs}} \quad (2.1)$$

This volume fraction is significant when calculating the final fibre volume fraction of the composite

$$V_f = V_{f,s}V_S \quad (2.2)$$

where V_S is the strand volume fraction in the unit cell (in the composite). [9]

Strands are formed when the yarns are mixed with the matrix, and the binding material penetrates the reinforcement bundle. This happens either during the moulding processes or when creating prepregs. Prepreg is a composite material in which the reinforcement is pre-impregnated with a matrix, i.e. before starting the moulding process of a part. The extent of prepreg materials in the composite industry is increasing due to their consistent properties, high quality surface finish and mainly due to their ease of use, i.e. less number of items to keep apart for the client [10].

2.2.1 Textile composites

Unlike in unidirectional plies⁴, in textile composites the fibres are oriented in more than one direction. Generally textile composites are divided into three types, depending on the techniques used to create the reinforcement mat. These are woven fabrics, knitted fabrics and braided fabrics. In this paper only the woven textile is of interest, for a deeper understanding of braided and knitted fabrics see [12]. In brief, the knitted and braided fabrics are to prefer for complicated shapes and have better impact resistance than woven fabrics, whilst woven fabrics have a higher fibre volume fraction, giving them better in-plane mechanical properties.

Woven fabrics are the most commonly used form. The textile consists of two interlaced yarn components, known as warp and weft, and is produced mainly by the multiple warp weaving method. The warp yarns run lengthwise and the weft yarns run crosswise in the fabric. Two dimensional woven fabrics are commonly divided into plain, twill and satin weaves, and are identified by their respective repeating patterns, see Figure 2.2.

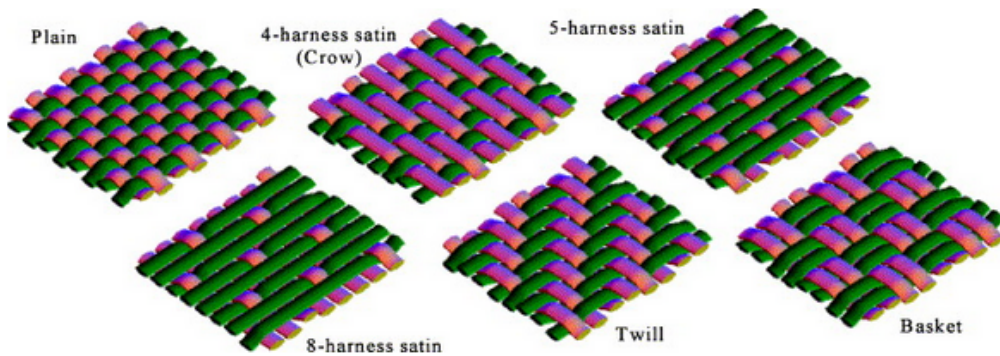


Figure 2.2: The figure represents the most common woven textile fabrics; plain, twill, satin and basket weaves [13].

In plain weaves, each warp yarn passes alternately under and over each weft yarn, making the fabric symmetric. Plain weaves have good stability and are the most used woven reinforcement. Twill weaves are recognised by a diagonal line created by the weaving technique. In the weaving structure, a warp yarn alternately floats

⁴A unidirectional lamina is a material where all the fibres are oriented in a single direction [11].

over two and under one weft yarn in a regular repeated manner, giving a looser interlacing than for plain weaves. Satin weaves differ from twill weaves in the way that they have fewer intersections, giving them good drapability⁵, a smoother surface and minimum thickness. In the satin weave, one warp yarn is woven over three or more weft yarns represented by the “harness” number, and then under one weft yarn. Satin weaves can be packed very tight and have lower crimp⁶ resulting in good mechanical properties. Drawbacks are the low stability and asymmetry, which when assembling multiple layers can cause that stresses are built into the component [12, 14].

In Figure 2.2, there is a fourth weave type by the name Basket, which basically is the same as a plain weave, except that two or more warp yarns alternately interlace with two or more weft yarns. The arrangement of the yarns does not have to be symmetrical, the amount of weft and warp yarns can differ in the fabric. Basket weave is flatter and stronger than a plain weave, but less stable. [14]

One usually distinguishes between opened-packing weaves and closed-packing weaves. In the first type mentioned there are gaps between two neighbouring yarns, whilst in a closed-packing weave the yarns are tightly woven, diminishing the gaps. Another classification used for weaves is whether or not the weave is balanced and it refers to if the fabric has the same properties and geometric dimensions in both the warp and weft directions.

Parameters that affect the mechanical properties of textile reinforced composites are weave architecture, yarn dimensions, yarn spacing (gap), yarn fibre volume fraction, together with the influence on laminate level, i.e. stacking orientation and overall fibre volume.

Major advantages with woven fabrics are good stability in the warp and weft directions, good formability, higher cover or yarn packing density and higher out-of-plane strength⁷ compared to other textile composites. On the other hand, they are anisotropic, have poor in-plane shear resistance, and are less suited for deep draw moulding than knitted or braided weaves due to their poor extensibility. [12]

There are three-dimensional woven fabrics as well. These have an additional yarn placed in through-the-thickness direction [12]. Stig and Hallström, found that, compared to traditional 2D laminates, the 3D weave has higher out-of-plane properties, lower risk for delamination⁸, better ability to produce various types of cross-sectional shapes [15], whilst lower values were observed for the in-plane stiffness and strength [16]. 3D fabrics will not be further discussed here and interested readers are referred to Stig and Hallströms articles [15] and [16].

2.2.2 Stack-up

Unidirectional plies are good load carriers in one direction, while e.g. a plain weave fabric has the ability to take up load in two directions. Nevertheless, there are few structures that have loads in a single or two directions, even though one direction may dominate. For that reason, multiple plies are stacked with different fibre orientation direction, to create a *laminated*. To achieve the most efficient composites for a structure, the majority of the fibres should be oriented in the primary load direction, whilst just enough fibres should be oriented in the other directions to carry secondary loads and hold the structure together [2].

2.2.3 Crimp

Fibres are most efficient when kept straight. Therefore, so-called yarn crimp is one of the parameters with great influence on the composite stiffness. It is commonly expressed as the ratio between the yarn amplitude and wavelength [9]. An alternative definition often used for crimp is the ratio between the yarns physical length along its path over one wavelength. Two-dimensional yarn crimp has been studied and published for unidirectional laminates by several research groups. Chan and Wang [15] focused on UD lamina and stacked laminates with different yarn waviness, whilst Stig and Hallström developed models with focus on the influence of yarn crimp on the longitudinal stiffness. Chapman and Whitcomb [16] found that yarns with high waviness, i.e. high crimp, are more sensitive to yarn architecture variations than yarns with low waviness. The stiffness decreases with increasing crimp [9].

⁵Ability to form around complex shapes.

⁶Crimp influences the composite material properties negatively.

⁷Out-of-plane strength carries the secondary loads due to load path eccentricity, local buckling, etc.

⁸Delamination is a composite failure mechanism, the separation of a laminate into layers.

2.3 TeXtreme Spread Tow fabrics

The TeXtreme fabrics are manufactured using OXEON's unique spread tow tape weaving technology. This technology enables the possibility to produce an ultra-light composite, thanks to the very thin fabrics, see Figure 2.3. Areas where the material already is being used in are racing, aerospace, marine, automotive industry, industrial applications and sport equipment. By spreading the tows (circular/elliptic yarn) into very thin tapes, the fibres become more packed, the crimp is decreased and the amount of interlacing points reduced, see Figure 2.4 . This results in a fabric with close to no waviness and less space for the matrix which results in a higher fibre content in the composite compared to conventional reinforcements.

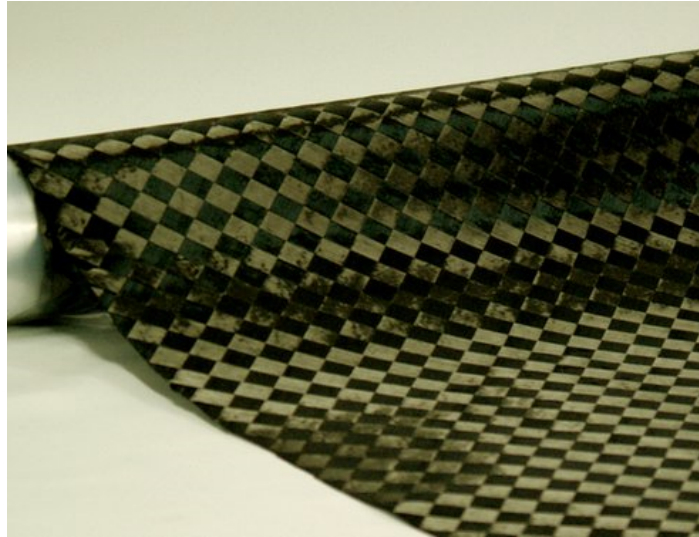


Figure 2.3: *An example of a very thin TeXtreme fabric [17].*

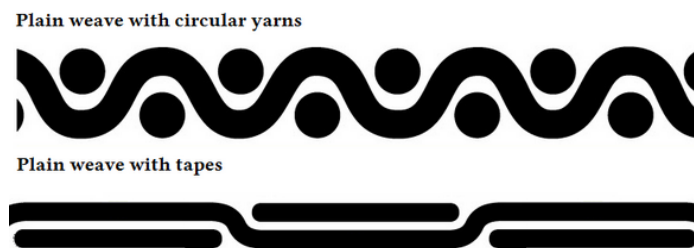


Figure 2.4: *Representative cross-section of two plain weaves, woven with conventional tows and OXEON's tapes respectively, showing the interlacing points.*

Some advantages with the TeXtreme material, for instance:

- **Weight reduction** - the increased fibre content gives better performance per weight
- **Increased mechanical properties** - in flat structures, the negative influence of crimp is minimised
- **Surface finish** - the flat weave with few interlacing points and small crimp gives a smooth surface
- **Tailored fabrics** - the TeXtreme fabric can be configured to give the desired properties by changing the materials, areal weight, fibre types, fibre angle, fibre distribution, tape width and fabric width.

As mentioned above, the TeXtreme material can come in many different shapes. In this project, the TeXtreme-100 is closer investigated. TeXtreme-100 is a plain weave and the manufacturing of this particular variant starts with the spreading of the tows, with approximately 15,000 filaments, into tapes with the dimension 20 x 0.05 mm. Thereafter a binder is added to stabilise the tapes. After that, the tapes are woven together to form a checker pattern with squares of 20 x 20 mm, see Figure 2.5. The total thickness of one laminate becomes 0.1 mm, and a binder is added to stabilise the fabric. Finally the fabric is rolled up on a roll.

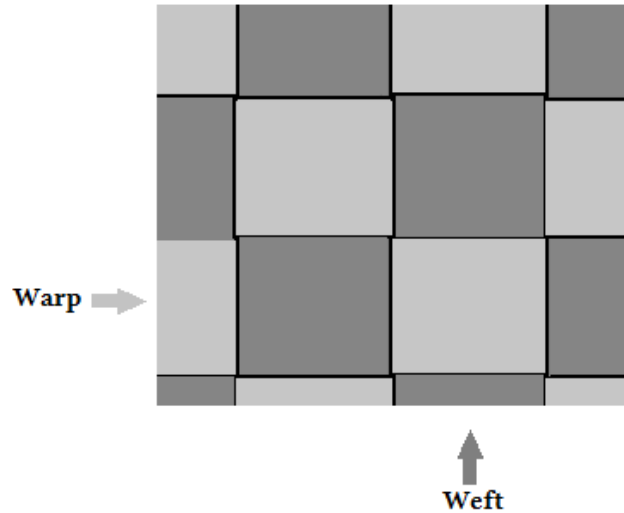


Figure 2.5: *An illustration of the TeXtreme checker pattern.*

2.4 Manufacturing methods for composite parts

In this subsection an overview of commonly used manufacturing methods for continuous fibre composites is given. The manufacturing method plays a large role in the final quality of the part.

Hand layup

The layup with the fabric is built on a mould by hand. The matrix can be added to the fabric either before the layup is built on the mould (i.e. wetting the fabric before or using prepreg) or afterwards. Curing is performed in normal temperature without added pressure. Hand layup is used during manufacturing of large products or products without the need of high performance material properties. The process cost is low compared to others. [18]

Vacuum bag moulding

A layup is first placed on a mould and then the composite layup is cured inside a vacuum. The added pressure from the vacuum bag increase the mechanical properties and reduce the defects of air bubbles. The vacuum bag moulding process is used during manufacturing of small to medium size products. [18]

Autoclave moulding

After the layup is set on a mould it is placed inside a pressurised and temperature controlled container while curing. The pressurised oven is called an autoclave. By having both pressure and temperature control a better quality is gained, with less defects which results in higher mechanical properties for the composite. Autoclave moulding is a process used for e.g. high-performance parts used for racing, aircrafts, spacecrafts and sport equipment. The quality of the parts are very good and consistent but it is an expensive process. [19]

Liquid composite moulding

The layup is done with dry reinforcement on to the mould and is then placed inside a vacuum bag. The matrix is then added by being pushed or sucked through the layup until the layup is saturated. Liquid composite moulding is for example used for boats, offshore structures, vehicle body panels and airplane parts. High performance parts can be manufactured with this method. [19, 20]

2.5 Calculating methods for mechanical properties

In this subsection, the equations used for predicting the mechanical properties of the impregnated yarns are presented. Due to the flat structure of TeXtreme there is virtually no crimp and the yarns are therefore assumed to be straight throughout the whole fabric. Thus the yarn (tape) is seen as a unidirectional lamina.

Thereafter the main engineering constants needed for modelling the Representative volume element (RVE) in ABAQUS CAE are presented. An RVE is a small section of the material often used for computational homogenisation techniques. The RVE is sufficiently large to contain all necessary information of the microstructure, but small enough to save computational time⁹ [21]. Finally the constitutive characterisation matrix, [ABD] matrix, is presented and Karkkainen's approach for finding the materials properties is given.

2.5.1 Impregnated yarn (strand) properties

All equations presented here are taken from [22] and are based on conventional laminate composite theory, if nothing else is stated. The longitudinal stiffness of a unidirectional ply is calculated from the Rule of mixture

$$E_L = V_f E_f + V_m E_m \quad (2.3)$$

where V_f is the fibre volume fraction in the lamina, E_f and E_m the Young's modulus of the fibre and matrix respectively. Observe, that for the strand's properties $V_{f,s}$ is used instead of V_f . When using the equation, the same strain for both the fibres and the matrix is assumed

$$\epsilon_c = \epsilon_f = \epsilon_m. \quad (2.4)$$

A method for calculating transverse stiffness and in-plane shear modulus for composites has been proposed by Halpin and Tsai. The equation for transverse stiffness modulus reads

$$E_T = E_m \frac{1 + \xi_E \eta_E V_f}{1 - \eta_E V_f} \quad (2.5)$$

where

$$\eta_E = \frac{\frac{E_f}{E_m} - 1}{\frac{E_f}{E_m} + \xi_E} \quad (2.6)$$

and for circular fibres it is suggested to use

$$\xi_E = 2. \quad (2.7)$$

The in-plane shear modulus, under the assumption of linear shear stress-shear strain behaviour and equal shearing stress on the fibres and the matrix, can be calculated according to Halpin and Tsai with

$$G_{LT} = G_m \frac{1 + \xi_G \eta_G V_f}{1 - \eta_G V_f} \quad (2.8)$$

where

$$\eta_G = \frac{\frac{G_f}{G_m} - 1}{\frac{G_f}{G_m} + \xi_G} \quad (2.9)$$

and it is suggested to use

$$\xi_G = 1. \quad (2.10)$$

The quantities G_f and G_m represent the shear modulus of the fibre and of the matrix respectively. For the homogeneous isotropic matrix material, the simple relations between elastic constants can be used to determine the shear modulus

$$G_m = \frac{E_m}{2(1 + \nu_m)} \quad (2.11)$$

where ν_m is the Poisson's ratio of the matrix. The shear modulus for the fibre can be calculated in the same way, if the filament is assumed isotropic,

$$G_f = \frac{E_f}{2(1 + \nu_f)} \quad (2.12)$$

⁹Computational time increases with model size.

where ν_f is the Poisson's ratio of the fibre. Worth mentioning is that even though the data sheet only list one stiffness for a fibre, E_f , it should not be interpreted to mean that the fibre is isotropic. The reason is the difficulty of performing experimental tests on the transversal direction of a fibre or a yarn, to gather test data. Meaning that the stiffness found in data sheets actually is the longitudinal stiffness of the fibre. In [23] an equation is given for calculating G_f , taking the anisotropic material into account,

$$G_f = \frac{E_f E'_f}{E_f + E'_f + 2\nu_f E'_f} \quad (2.13)$$

where E'_f is the transverse fibre stiffness. This stiffness can be approximated as a tenth of the longitudinal stiffness [24, 25]. It can be seen that equation 2.12 equals to equation 2.13 if $E_f = E'_f$, meaning isotropic material.

Further, the major Poisson's ratio is also determined using the rule of mixtures

$$\nu_{LT} = \nu_f V_f + \nu_m V_m \quad (2.14)$$

whilst the minor Poisson ratio can be obtained from the relation between stiffness E_L and E_T and the Poisson ratios ν_{LT} and ν_{TL}

$$\nu_{TL} = E_T \frac{\nu_{LT}}{E_L}. \quad (2.15)$$

The transversal shear modulus, G_{TT} , and transversal Poisson's ratio, ν_{TT} , for the yarn are calculated as [26]

$$G_{TT} = \frac{G_m}{(1 - \sqrt{V_{f,S}})(1 - \frac{G_m}{G_f})} \quad (2.16)$$

$$\nu_{TT} = \frac{E_T}{2G_{TT} - 1}. \quad (2.17)$$

2.5.2 Main engineering constants

The generalised Hooke's law [22] is the most general linear relationship that relates stress to strain and can be expressed as

$$\sigma_{ij} = E_{ijkl} \epsilon_{kl} \quad (2.18)$$

where E_{ijkl} is a fourth order stiffness tensor, σ_{ij} the stress tensor and ϵ_{kl} the strain tensor, the two latter both having nine components. Thus there are 81 elastic constants defining the tensor E_{ijkl} . However, symmetry conditions and thermodynamic considerations reduce the number of independent elastic components for an anisotropic material to only 21. This, in turn, is reduced to nine for orthotropic materials and five for transversely isotropic materials (same properties in two of the directions).

Generally, for unidirectional composites 1 corresponds to the fibre direction in-plane, 2 transverse to the fibre in-plane and 3 perpendicular to the plane. A unidirectional lamina is approximately transversely isotropic meaning that the following relations exist [27]

$$E_{33} = E_{22} \quad (2.19)$$

$$G_{13} = G_{12} \quad (2.20)$$

$$\nu_{13} = \nu_{12} \quad (2.21)$$

$$E_{22} = 2(1 + \nu_{23})G_{23} \quad (2.22)$$

and for orthotropic symmetry

$$\frac{\nu_{12}}{E_{11}} = \frac{\nu_{21}}{E_{22}} \quad (2.23)$$

$$\frac{\nu_{23}}{E_{22}} = \frac{\nu_{32}}{E_{33}} \quad (2.24)$$

$$\frac{\nu_{13}}{E_{11}} = \frac{\nu_{31}}{E_{33}}. \quad (2.25)$$

With these material relations and the strand properties known, the main engineering constants needed for modelling the RVE in ABAQUS CAE read

$$E_{11} = E_L \quad (2.26)$$

$$E_{22} = E_{33} = E_T \quad (2.27)$$

$$G_{12} = G_{13} = G_{LT} \quad (2.28)$$

$$\nu_{12} = \nu_{13} = \nu_{LT} \quad (2.29)$$

$$\nu_{23} = \nu_{TT} \quad (2.30)$$

$$G_{23} = G_{TT} = \frac{E_{22}}{2(1 + \nu_{23})}. \quad (2.31)$$

2.5.3 Constitutive characterisation matrix

The constitutive characterisation matrix ($[ABD]$ matrix) can be seen as three separate matrices containing material information. The first matrix, $[A]$, is the extensional stiffness matrix

$$\begin{bmatrix} A_{11} & A_{12} & A_{16} \\ A_{12} & A_{22} & A_{26} \\ A_{16} & A_{26} & A_{66} \end{bmatrix}.$$

The terms relate the normal stresses and strains, except for the A_{16} and A_{26} terms which relate shear strain to normal stresses and normal strain to shear stresses. The units of elements in the $[A]$ matrix are those of stress times length. The second matrix, $[B]$, is called the coupling stiffness matrix

$$\begin{bmatrix} B_{11} & B_{12} & B_{16} \\ B_{12} & B_{22} & B_{26} \\ B_{16} & B_{26} & B_{66} \end{bmatrix}.$$

The B_{11} , B_{22} , B_{12} and B_{66} terms relate bending strains (plate curvature) with normal stresses and vice-versa, whilst B_{16} and B_{26} relate twisting strains to normal stresses and shear strains to bending stresses. The presence of this matrix implies coupling between bending and extension of a laminated plate, for a symmetric laminate all the terms in the $[B]$ matrix are zero. The units of elements in the $[B]$ matrix are those of stress times length squared. The last matrix, $[D]$, is the bending matrix

$$\begin{bmatrix} D_{11} & D_{12} & D_{16} \\ D_{12} & D_{22} & D_{26} \\ D_{16} & D_{26} & D_{66} \end{bmatrix}.$$

The terms relate the amount of plate curvatures with the bending moments. The units of elements in the $[D]$ matrix are those of stress times length cubed. [28]

2.5.4 Karkkainen approach

Karkkainen's approach to evaluate the elastic properties of an RVE of a plain weave textile composite, see Figure 2.6, is here only briefly presented; for a full derivation see the doctoral thesis [29]. The method is based on a square shaped RVE ($a = b$), with the origin placed in the centre point of the RVE. The Karkkainen method is used to compute the $[ABD]$ matrix, explained in Section 2.5.3, directly by using the direct micromechanics method (DMM), with no need of making estimations based upon homogenised properties, see Section 2.6.

Six cases are studied. E.g. for case 1, an elongation in the x_1 direction is set to 100%, by doubling the length in the x_1 direction (using displacement boundary condition) and preventing any displacement in the other in-plane direction (x_2 -direction). Furthermore, there are no constraints in the out-of-plane direction (x_3 -direction). This equals to an applied strain in the elongated direction, $\epsilon_{x_1} = 1$, whilst all other strains and curvatures are zero. In Table 2.1 the six cases and their corresponding periodic boundary conditions (PBC), see Section 2.5.4.1, are presented. Column two represents the strain or curvature prevailing for each specific case, whilst all other strains and curvatures are zero

$$\epsilon_y = \gamma_{xy} = \kappa_x = \kappa_y = \kappa_{xy} = 0 \quad (2.32)$$

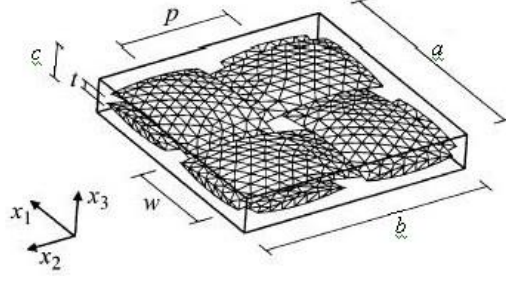


Figure 2.6: RVE geometry of a plain weave textile composite [29].

Table 2.1: Periodic Displacement Boundary conditions (M is short for macro).

Case		$u(a,y)-$ $u(0,y)$	$v(a,y)-$ $v(0,y)$	$w(a,y)-$ $w(0,y)$	$u(x,b)-$ $u(x,0)$	$v(x,b)-$ $v(x,0)$	$w(x,b)-$ $w(x,0)$
1	$\epsilon_x^M = 1$	a	0	0	0	0	0
2	$\epsilon_y^M = 1$	0	0	0	0	b	0
3	$\gamma_{xy}^M = 1$	0	a/2	0	b/2	0	0
4	$\kappa_x^M = 1$	az	0	$-a^2/2$	0	0	0
5	$\kappa_y^M = 1$	0	0	0	0	bz	$-b^2/2$
6	$\kappa_{xy}^M = 1$	0	az/2	-ay/2	bz/2	0	-bx/2

where ϵ_y is the strain in x_2 -direction, γ_{xy} the in-plane shear strain, κ_x the curvature in x_1 -direction around x_2 -axis, κ_y the curvature in x_2 -direction around x_1 -axis and κ_{xy} the twist in the x_1 - and x_2 -direction around respectively axes. In the table, the columns three to five represent the displacements in x_1 , x_2 and x_3 direction for the planes parallel to the x_1 direction, whilst column six to eight represent the displacements in the three directions for the planes parallel to the x_2 direction. The quantities u, v and w in Table 2.1, are the displacements in x_1 , x_2 and x_3 directions respectively, and x, y, z correspond to x_1 , x_2 and x_3 in Figure 2.6.

The relation between the macroscopic force, N , and moment, M , resultants and the macroscopic strain, ϵ^M , and curvature, κ^M , is used to evaluate the $[ABD]$ matrix. This approach simplifies the solving of the $[ABD]$ matrix significantly

$$\begin{bmatrix} N \\ M \end{bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} \begin{bmatrix} \epsilon \\ \kappa \end{bmatrix}.$$

since the columns of the $[ABD]$ matrix can be solved for separately for with each case.

The FEM results from each of the cases yield the micro-stresses for all the elements, σ_{ij}^e , resulting from an applied macro-level strain and curvature. The macro-level forces per unit length, N , and moments per unit length, M , can in turn be computed for each case by averaging the micro stresses over the entire volume of the RVE

$$N_{ij} = \frac{1}{ab} \sum (\sigma_{ij}^e V^e) \quad (2.33)$$

$$M_{ij} = \frac{1}{ab} \sum (z \sigma_{ij}^e V^e) \quad (2.34)$$

where V^e is the volume for element e .

2.5.4.1 Periodic boundary conditions

In order to predict properties of the heterogeneous materials using the finite element method on an RVE, periodic boundary conditions are applied. This to ensure continuity of micro stresses and compatibility of displacements across the RVE. Making the RVE mechanically repeatable in the sense that each RVE has an identical response to strains and curvatures irrespectively of the location of the RVE in a textile component. The PBC can be applied by connecting the degrees of freedom of nodes on one surface to the corresponding nodes on the opposed surface, for this an identical mesh on both sides is required. [21]

2.6 Homogenisation of the composite material

Homogenisation is an efficient technique used to calculate and predict the macroscopic behaviour of composite materials. Two steps are needed to capture the macroscopic response of heterogeneous materials. The first step is to solve the Eshelby problem, which is to solve the problem with the inclusions embedded in the infinite reference homogeneous medium also called localisation problem. The second step is to connect the local fields to the global also called averaging. [30]

Eshelby's inclusion problem

John D. Eshelby proposed a theory for how to solve the problem with inclusions embedded in an infinite homogeneous reference material. The result from his solution was strain, stress and deformation fields for both inclusion and matrix. A derivation for this can be found in [31]. This method is widely used in other solving methods. For linear elasticity, the Eshelby problem has an exact solution but it has no analytical solution for non-linear behaviours. Numerous different homogenisation schemes for different materials have been proposed based on Eshelby's inclusion problem.

The four schemes/solvers offered by the composite software WiseTex are presented below.

Mori-Tanaka

The Mori-Tanaka solving method is a fast solving method with good overall accuracy. The method is commonly used for composite materials where the matrix can be clearly identified. It can be used to predict the elastic properties, calculate thermal stresses and plastic deformation. The method is also used for modelling of damage and strength of composites. The Mori-Tanaka method gives explicit formulae for the effective stiffness tensor and for the local stresses and strains. This explicit character is probably one of the reasons why the Mori-Tanaka method is so commonly used. [32]

Self-Consistent

The self-consistent method is an implicit scheme and uses an iterative process while solving for the properties in question. This makes the self-consistent method much slower than the Mori-Tanaka method. The self-consistent method predict the shear modulus better than the Mori-Tanaka method in composites with a higher fibre content. [33]

Iso-strain (FGM) (Voigt)

The method uses an approximation of constant strain in the composite and uses the rule of mixture for stiffness components. It is marginally faster than the Mori-Tanaka method but less accurate. [23]

Iso-stress (Reuss)

The method uses an approximation of constant stress through the composite. It is not used for long fibre composites but can be used for particle based and short fibre materials. [23]

3 Method

For better understanding of the material behaviour the project started with a literature study about basic composites knowledge, orthotropic and anisotropic material behaviour, as well as micro mechanics, strength of materials and composite testing. The following step was measuring the TeXtreme-100 weaves for determination of material dimensions, which are needed for the simulation work. The final part of the project consisted of simulation work on an RVE to obtain results for verification and comparison to existing test data.

This chapter ends with a clarification of which methods (software path), presented in Section 3.2, are chosen for the TeXtreme-100 RVE.

An additional part to the project is macro simulation of a floorball shaft exposed to external load and was performed in ABAQUS CAE. The background, the theory and the approach for this part are presented in Chapter 4.

3.1 Measuring of TeXtreme material dimensions

Datasheet values for the tape width, the spacing and the thickness are available. These are however only guidelines for the geometry. Hence the TeXtreme-100 material is measured by hand to get the dimensions of the manufactured fabric and to get an estimation of the manufacturing tolerances.

3.1.1 Thickness measurement

The yarn thickness is determined from microscope pictures similar to the one in Figure 3.1. It is obtained by measuring the thickness for a number of plies and then computing a mean value for the layer thickness. Data provided from the SICOMP test of TeXtreme-100 fabric is also used to find an average tape thickness [34]. The data from the SICOMP test give a mean thickness value for a laminate, this can be used to calculate the mean thickness of a ply since the amount of plies in the layup is known.

A mean strand width is determined, using the warp and weft width values (see Section 3.1.2), and multiplied with half of the ply thickness to determine a default cross section area

$$A_{cs,d} = \left(\frac{d_{warp} + d_{weft}}{2} \right) \frac{t_p}{2} \quad (3.1)$$

where d is the width of the warp and weft respectively, and t_p the average thickness of the ply. The default cross section is used to compute the warp and the weft thickness

$$t_{warp} = \frac{A_{cs,d}}{d_{warp}} \quad (3.2)$$

$$t_{weft} = \frac{A_{cs,d}}{d_{weft}} \quad (3.3)$$

ensuring that the yarns have the same cross section area.

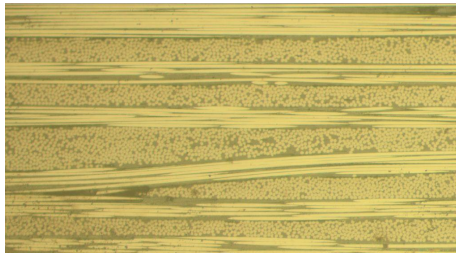


Figure 3.1: A microscopic picture of a TeXtreme-100 laminate [35].

3.1.2 Yarn width and spacing measurement

Three different batches of dry TeXtreme-100 material are used for the measuring of yarn width and spacing. An USB microscope has been used to take pictures on fairly randomly chosen parts of the fabric, represented by the white pieces of paper in Figure 3.2. Three meters of each material are studied, with 30 cm distance between the sections, where each section has in turn has three randomly chosen parts. On each measurement



Figure 3.2: *One of three TeXtreme-100 batches used for yarn width and spacing measurement.*

point two measurements are performed both for the warp and the weft yarn width and spacing, see Figure 3.3. To calibrate the dimensions in the picture, a calliper is used as reference. Min, max, mean and median values for the warp and weft yarn width and spacing are determined using MATLAB. To rule out extreme irregularities, values differing more than five percent from the median are weed out. A clarifying image on what is meant with yarn thickness, width and spacing is found in Figure 3.4.

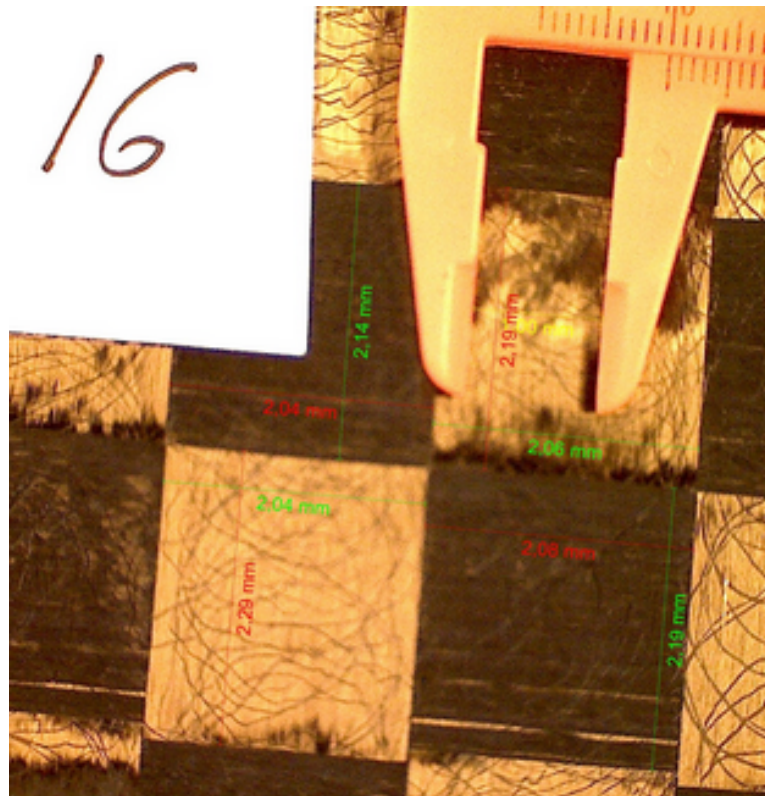


Figure 3.3: Visualisation on how the width and the spacing measurements are performed.

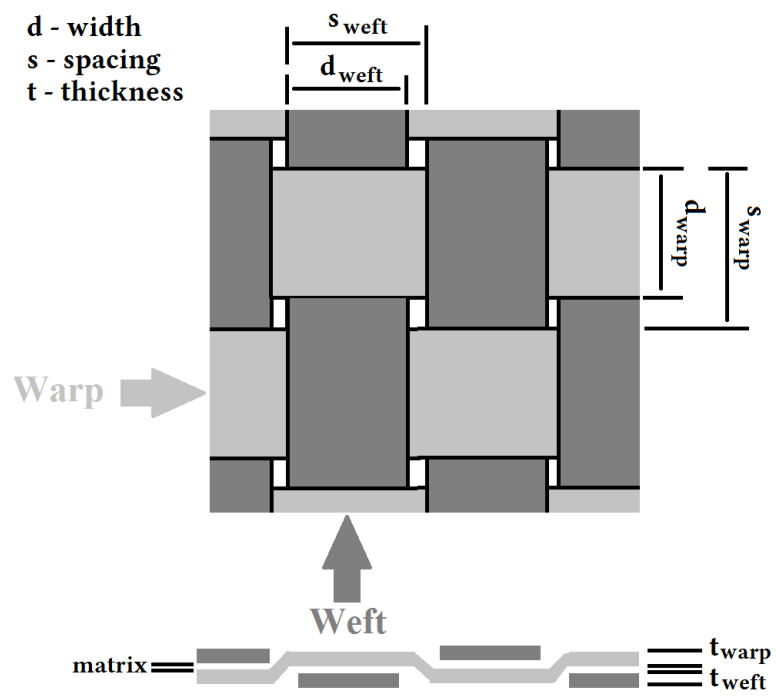


Figure 3.4: Illustration of yarn thickness, width and spacing.

3.2 Software usage

Different approaches were tested to reach values that meet the experimental data. In Figure 3.5 a schematic sketch presents the interaction between the softwares used. Each program will be briefly explained in the subsections below.

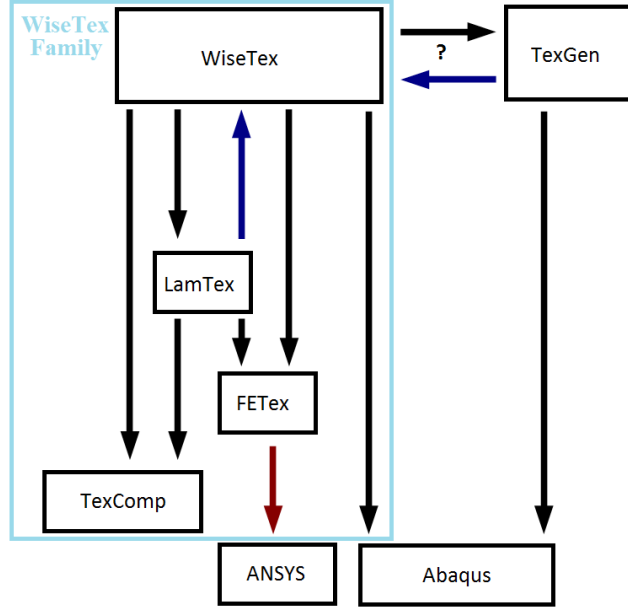


Figure 3.5: *Schematic sketch showing the interaction between the software.*

There are a number of research groups using the interaction between the two geometry building programs WiseTex and TexGen, such as Stig and Hallström [16]. Sadly, the steps from WiseTex to TexGen and vice versa could not be performed, due to insufficient information about the procedures, which is unfortunate since some features missing in one of the programs can be found in the other.

The two paths that proved to be most useful in this study are: WiseTex to TexComp, for obtaining fast analytical results, and WiseTex to ABAQUS CAE for a numerical, more time¹⁰ consuming, analysis.

3.2.1 WiseTex family

The software family WiseTex (WiseTex, LamTex, FETex and TexComp)¹¹ proved to be intuitive and user friendly. Unfortunately, the version WiseTex 3.1 being used is in a beta stage and contains bugs and unfinished sections. What is done in the subprograms is shortly presented below.

3.2.1.1 WiseTex

In WiseTex the unit cell is built by choosing textile type, defining yarn parameters and giving the mechanical properties of the fibre. No matrix is taken into account in the program. It can be seen as starting at a micro scale, the filament level, and obtaining an RVE at meso scale¹². The program returns fibre volume fraction both for the strands and the unit cell, areal density, porosity¹³, unit cell size, and yarn information such as dimensions and crimp. WiseTex allows the user to control in detail the unit cell by offering a number of options for the fibres and yarns. Influence of the various parameters are discussed in Section 5.3.1.

¹⁰Longer processing time including modelling and solving time.

¹¹Provided by Professor Stephan Lomov with associates at KU Leuven.

¹²Meso scale corresponds to approximately the size of an RVE.

¹³Porosity in a unit cell corresponds to the area where the matrix will lie in a finished lamina, not including the matrix in the strands.

3.2.1.2 LamTex

If a ply has high crimp and waviness it can be of interest to stack the layers with a shift so that better nesting and smaller gaps between the laminas are obtained. In LamTex the fitting of the layers to one another can be modified and a laminate can be built. Since the TeXtreme fabric is extremely flat compared to regular fabrics, it has poor nesting [36] and therefore the subprogram adds nothing to the result and has therefore not been used.

3.2.1.3 FETex

In this program, a script is written that is used to export the fabric created in Wisetex to ANSYS Classic. In this step, the matrix is taken into consideration and its mechanical influence is added to the dry yarn, returning the strands mechanical properties. An option given in FETex is the shrinking of the strands cross section, so that penetration of the yarns will not become a problem when simulating the geometry. The program recalculates the strands properties so that the final fibre fraction is not affected by the areal change. However, the program can not be used for what it is intended, due to problems with exporting the composite models. On the other hand, the information about the impregnated yarns is still useful when creating the strand in ABAQUS CAE, more explained in Section 3.2.3.

3.2.1.4 TexComp

TexComp is the solving part of the WiseTex family. Here the matrix is added to the dry fibre textile, created in WiseTex or LamTex, not only impregnating the yarns but also filling the porosity mentioned earlier. The composite material is then homogenised using an analytical solving methods and the stiffness, shear and Poisson's ratio of the fabric are calculated. The solvers available are Mori-Tanaka, Self-Consistent, Iso-strain and Iso-stress, and have been presented in Section 2.6.

3.2.2 TexGen

TexGen is an open source software used for modelling the geometry of textile structures¹⁴. In the program an RVE is built by choosing the strands architecture and then adding a domain to represent the matrix. The strands and matrix mechanical properties can also be set in the program or left empty and introduced in the FEM-solving program. The model must be exported to an external FEM solver to gain results. TexGen is easy to use with only a few parameters needed to create a geometry that can be exported as a Step file¹⁵ to ABAQUS CAE. The model can also be exported as an input file which can be run with ABAQUS Command.

3.2.3 ABAQUS CAE

ABAQUS CAE is used to model the RVE of a composite material with the purpose to evaluate and determine the stiffness and strength of the material. The Karkkainen [29] approach to determine the $[ABD]$ matrix for a composite is implemented by modeling six different strain/curvature cases for the RVE. Instead of using 100% strain and curvature respectively, as suggested by Karkkainen, 1% strain and curvature are used. This, seeing that 100% is unrealistic and also results in values further from the experimental ones.

3.2.3.1 Simple box

First a simple model is created with the purpose to develop a step-by-step method for determining the $[ABD]$ matrix. The model consists of a simple square shaped box, seen from the top, made out of one material, see Figure 3.6.

The geometry is built inside ABAQUS CAE, using reduced¹⁶ tetrahedral elements and the material is defined using Engineering constants. The simulation is run with non-linear geometry¹⁷ and boundary conditions are added according to Karkkainen. The periodic boundary conditions are implemented using a python script. The script connects nodes on one side of the RVE to the corresponding ones on the opposite side using equation

¹⁴TexGen is developed at the University of Nottingham.

¹⁵In a step file only the 3D model's geometry is exported, meaning without material properties.

¹⁶Reduced elements only have one integration point per element.

¹⁷Non-linear so that coordinates for deformed state can be found.

constraint. The cases are solved both with and without the script.

For the deformed state, the stresses in the integration points, the coordinates for the integration points and the element volumes are saved in rpt-files¹⁸ for further usage in MATLAB, see Section 3.2.3.4. The stiffnesses for the materials warp and weft direction are roughly calculated in ABAQUS CAE using the reaction forces on the surface opposite to the one where the displacement boundary condition is applied, using Hooke's law

$$\sigma = E\epsilon \quad (3.4)$$

with

$$\sigma = \frac{F}{A} \quad (3.5)$$

and

$$\epsilon = \frac{\Delta L}{L} \quad (3.6)$$

where F is the reaction force on area, A, and ΔL the elongation from the original length, L.

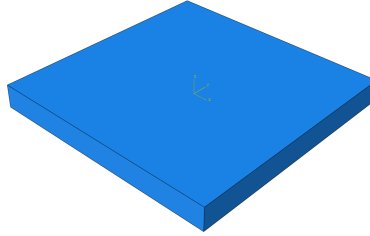


Figure 3.6: *The unit cell of the Simple box, created in ABAQUS CAE.*

3.2.3.2 Unidirectional composite

Thereafter, a more complex geometry is analysed. A simple composite model is built to verify if the method used on the simple box works on a composite material. A unidirectional material is built in ABAQUS and the $[A]$ matrix is determined using the MATLAB script as for the simple box in Section 3.2.3.1. The impregnated yarn properties of the unidirectional composite are defined using FETex. For this model the periodic boundary conditions cannot be used, due to the unequal mesh on opposed surfaces. The results are compared to the values gained using the Rule of Mixtures and Halpin and Tsai equations presented in Section 2.5.1 and the results obtained from a unidirectional model created in WiseTex. The geometry of the unidirectional RVE ABAQUS model is seen in Figure 3.7.

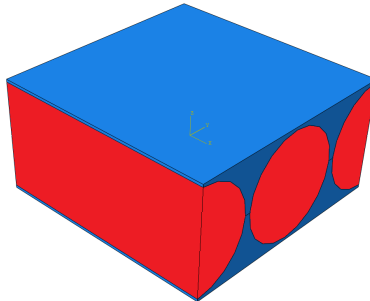


Figure 3.7: *The unit cell of the Unidirectional composite, created in ABAQUS CAE. The red colour represents the strand structure, whilst the blue illustrates the matrix.*

¹⁸Report file.

3.2.3.3 Plain weave

The final geometry, and the most complex one, is the plain weave RVE. The different approaches to create the geometry are described below. Once again, no periodic boundary conditions could be used, due to the same reason as for the unidirectional composite.

Importing geometry from WiseTex or TexGen

The geometry of a composite RVE can be built in WiseTex and TexGen as described in the previous sections. The geometry from WiseTex is imported to ABAQUS CAE by running a script that comes with the software¹⁹. In the script, the impregnated yarn properties are set (obtained from FETex), while the matrix is created in ABAQUS CAE. For a step-by-step demonstration on how a unit cell can be built see Appendix E.

The TexGen geometry on the other hand is imported as a model in ABAQUS CAE. Then, basically the same procedure is applied as for the WiseTex model. Problems that appear using these approach are presented in Section 5.3.1 and Section 5.4.

Building the geometry in ABAQUS CAE

Two parts are created representing a simplified warp and weft strand structure. In the Assembly module the parts are multiplied, translated and rotated to form the strands in the unit cell, see Figure 3.8. The matrix is created as in the previous cases. The cases are solved using both a discrete material orientation²⁰ and with a global orientation, which means that the crimp influence is neglected. The material engineering constants for the weft are converted to maintain the accurate stiffness orientation when using the global orientation, see Table 3.1.

Table 3.1: The engineering constants for the weft, applied in ABAQUS CAE. The first row represents the values for a discrete material orientation, and the last column represents the values for a global material orientation.

Engineering constant	E_{11}	E_{22}	E_{33}	ν_{12}	ν_{13}	ν_{23}	G_{12}	G_{13}	G_{23}
Discrete M.O.	E_L	E_T	E_T	ν_{LT}	ν_{LT}	ν_{TT}	G_{LT}	G_{LT}	G_{TT}
Global M.O.	E_T	E_L	E_T	ν_{TL}	ν_{TT}	ν_{TL}	G_{LT}	G_{TT}	G_{LT}

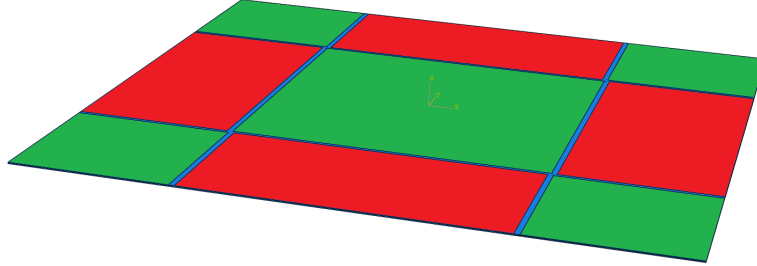


Figure 3.8: The unit cell of TeXtreme, created in ABAQUS CAE. The red and green colour represent the warp and weft respectively, whilst the blue illustrates the matrix.

3.2.3.4 MATLAB

The report file from ABAQUS is evaluated in MATLAB. A script has been developed to automatically read the report file, containing the stresses, coordinates and element volume sizes. It clears the data from text, converts the numbers from char to double and creates matrices of the values. The program returns the $[ABD]$ matrix, by applying the method developed by Karkkainen.

¹⁹The script is called WiseTex_to_Abaqus.py

²⁰When using discrete orientation, the strand's material orientation is following the curvature of the strand, see Appendix E.

3.3 Chosen software path

In Subection 3.2 all the tested approaches are presented. Here a clarification, of the two most suited software paths for evaluating the stiffness of the TeXtreme-100 material, is presented, see Figure 3.9. The two solid black arrows represent cooperation between the software, whilst the dashed black arrow represents information transport (no geometry is exported nor script written). The gray arrows represent the paths that are not used.

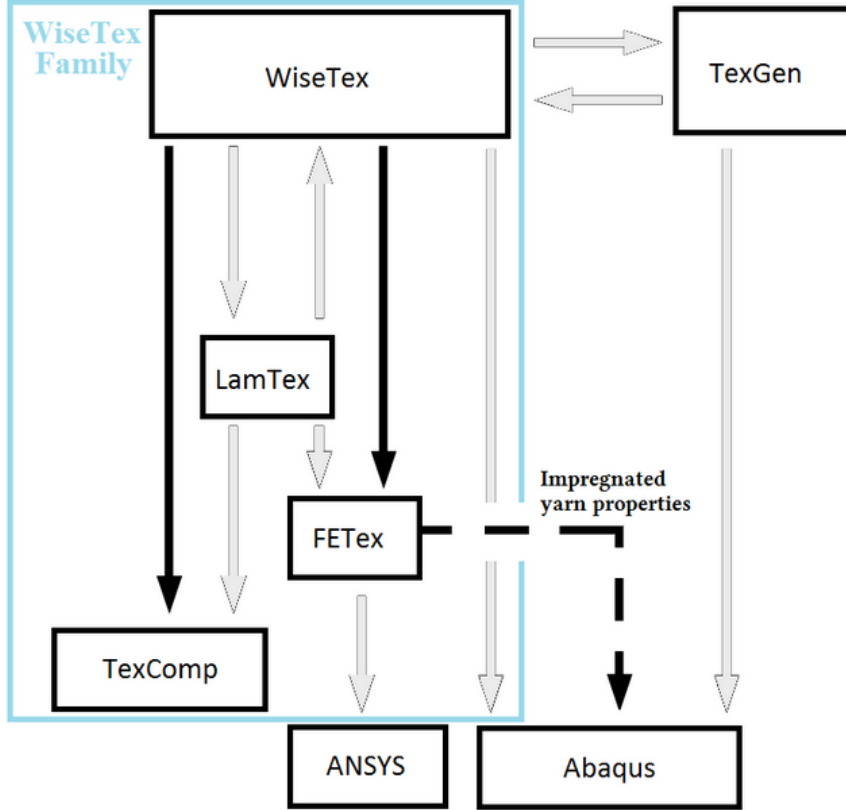


Figure 3.9: Schematic sketch showing the two most suited paths for stiffness evaluation of the TeXtreme-100 fabric.

One approach to obtain the Young's Modulus, Shear Modulus and Poisson's ratio is by building the geometry in WiseTex and using a homogenisation technique in TexComp. The other method is to create the whole unit cell in ABAQUS CAE and use Karkkainens approach to determine the $[ABD]$ matrix, using finite element instead of homogenisation. This by using the MATLAB script, which automatically reads the report file, containing the stresses, coordinates and element volume sizes. In the latter method, the longitudinal and transversal stiffness can also be roughly estimated with the reaction forces and Hooke's law, i.e. no need for MATLAB. A schematic sketch of these approaches and their input and output data is presented in Figure 3.10. The green arrow represents a possible method to determine the strand properties, another option would be to find these using hand calculations (Rule of mixture and Halpin and Tsai).

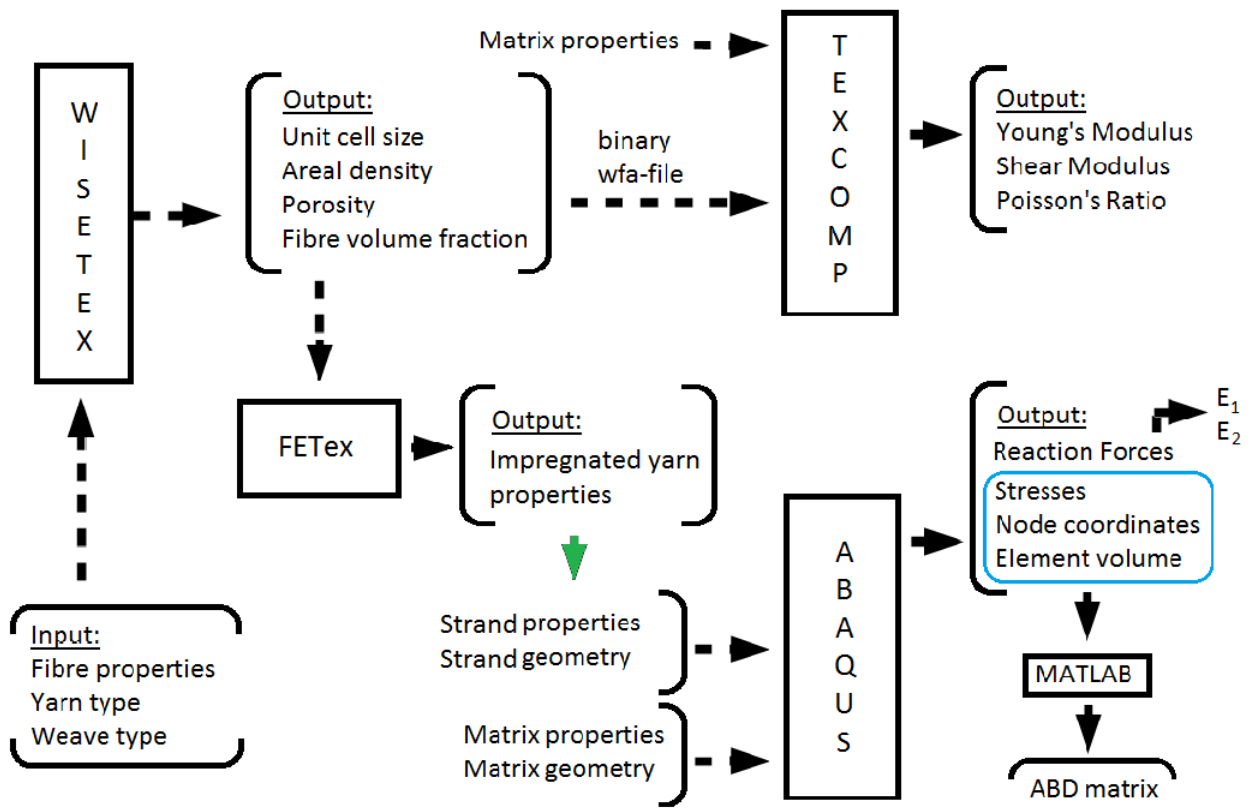


Figure 3.10: *Resumé-sketch for the two approaches used to evaluate the stiffness of the TeXtreme-100 material. The green arrow represents information transfer, no software cooperation.*

4 Application

With the intention to reduce the weight of their floorball sticks, a sports-company is considering the use of TeXtreme in the shaft. In this section a method to model and evaluate the item made out of TeXtreme-100 is presented.

4.1 Background

Due to the possibility to manufacture various kinds of shapes of a floorball stick at low cost and to test these, there are little, if any, optimisations done so far, using simulations and computational methods, for this particular product.

Today the shape of a floorball shaft is either straight, conical or curved, and the cross sections can be circular, oval or triangular. Shafts with features like ripples and non-constant geometry are also commonly used to improve the properties. There are two requirements set by the International Floorball Federation (IFF) for a 850 mm, or longer, floorball shaft, regarding deflection and deformation, see Section 4.3. These demands are safety-related and must be fulfilled to grant permission for the usage of the floorball stick during competitions. Furthermore, there are also requests from the players regarding the performance during usage.

4.2 Aim and limitation

The aim of this part of the thesis work is to develop a method that can be used for evaluation and design of a product made of TeXtreme fabric. If possible, also recommend a specific layup that results in a shaft, lighter than the ones existing today but still fulfilling IFF's criterion. The focus lies on a straight conical shaped shaft.

4.3 Requirements for the shaft

To evaluate whether or not the shaft meets the stiffness and strength requirements set by IFF, a three point deflection test is performed, see Figure 4.1. A universal testing machine with a velocity of 200 mm/min is used during testing. The shaft is placed on two rolls with 800 mm between the centres of the supports (red in Figure 4.1). The rolls are free to rotate around their axis of rotation, diminishing friction between shaft and rolls. A third, vertically movable roll (blue in Figure 4.1), is used for applying the force. Two test are performed; one

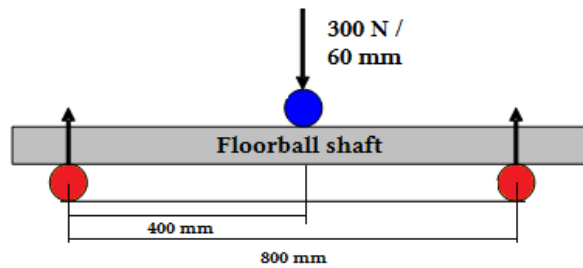


Figure 4.1: Illustration of the 3-point deflection test, with two (red) supporting rolls and one moving roll (blue).

when the moving roll applies a force of 300 N onto the shaft and the other when the moving roll adds a 60 mm deflection to the part. IFF formulates the requirements for the rigidity of the shaft as follows:

“The shaft should deflect by at least 23 mm under a load of 300 N measured as mean value of three deflections in each direction (horizontal and vertical). No individual value may be less than 20 mm for the most rigid direction of the shaft. The shaft should tolerate a deflection of at least 60 mm without cracking or fracturing. The shaft’s resulting deformation following deflection should not exceed 6 mm.” [37]

Meanwhile, the floorball company has their own preferences, more adapted to the customer request

- 26 mm deflection at 300 N
- 65 mm deflection before failing

4.3.1 Shafts made out of TeXtreme material

The manufacturer produced nine conical shafts using TeXtreme fabrics. For the shafts three different TeXtreme fabrics were used, which are presented in Table 4.1.

Table 4.1: TeXtreme material used on test samples.

Fabric	Areal weight [gsm]	Amount of fibres
TeXtreme-76	76	18000
TeXtreme-80	80	12000
TeXtreme-100	100	15000

Three types of shafts were manufactured out of each fabric. The first shaft type has the commonly used nominal standard thickness for existing shafts of 1.7 mm and consists of 100% TeXtreme fabric. The second type also has the same nominal thickness of approximately 1.7 mm, but consists of 50% TeXtreme fabric and 50% of the commonly used fabric in today's shafts. The third type is a thinner version of the first mentioned, with a standard thickness of 1 mm and 100% TeXtreme fabric. These shafts were subjected to the three point deflection test and the test results are presented in Appendix B.

4.4 Simulation

A brief description of the simulation method is presented here. The software ABAQUS CAE is used to simulate the shafts. Only the shafts made purely out of TeXtreme-100 fabric are analysed, since the stiffness and the strength are not known for the other fabrics.

4.4.1 Assumptions and Simplifications

The assumptions and simplifications made for the simulation model are presented below:

- The shaft geometry is assumed to have the shape of a truncated cone²¹ with constant diameter change. Measurements were performed during the three point deflection test, giving the diameter dimensions.
- The inner surface of the model of the shaft is modelled the same for all layups, since the same mould was used, i.e. meaning that the surface thickness is built outwards.
- For simplicity, the thickness is not considered when adding contact constraints.
- The fabric is assumed to have the same material properties as the one used at SICOMP when testing TeXtreme²².
- The influence of manufacturing defects is neglected.
- The thickness of one layer is assumed to be 0.092 mm²³.
- The fabric is assumed to be balanced and closed-packed, since the directions of warp and weft are unknown.
- Neither the influence of overlapping fabrics nor the angle change of the fibres, due to the changing diameter, are considered.

²¹The part of the cone that is left after it is cut by a plane parallel to the base and the apical part is removed.

²²The matrix used for the shafts is not provided by the manufacturer, therefore the assumption.

²³The mean value of SICOMP's calculated layer thickness and the layer thickness gained from the measurements on microscopic pictures.

4.4.2 The model

The geometries for the test rig and the shaft are created inside ABAQUS CAE, see Figure 4.2.

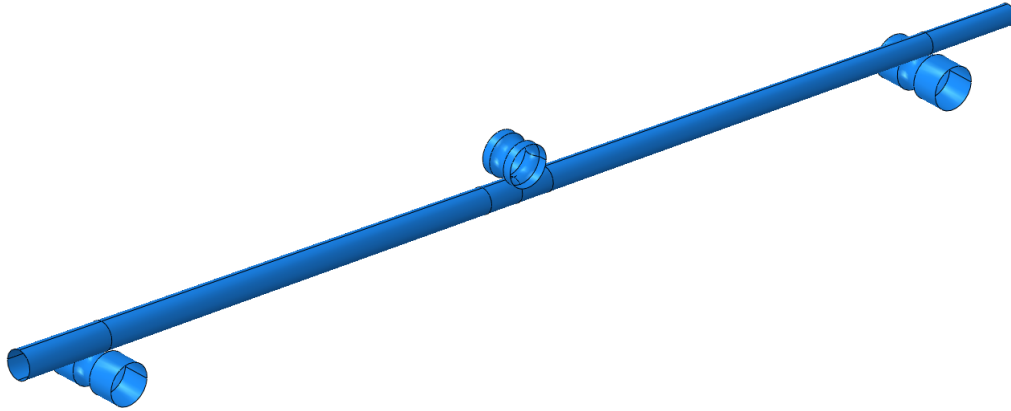


Figure 4.2: *ABAQUS assembly of the three point deflection test.*

Geometry

The conical shaft is built from a revolved shell whilst the rolls, corresponding to the test equipment, are built from revolved analytical rigid surfaces. The analytical rigid surfaces are used for the rolls, since no deformation is allowed on these parts. A rigid body constraint, using a reference point, is added on each analytical rigid surface to simplify the setting of the boundary conditions and the deflection measurements. The model is assembled without any gap between the parts.

Contact

Surface to surface interaction is used between the parts in the model to create contact between them. The tangent behaviour is chosen to be frictionless and the normal behaviour as “Hard” contact using penalty method.

Mesh

The shell of the shaft is meshed with linear quad elements. The region close to the moving roll is meshed with a smaller seed, due to higher stress concentrations. In the simulations an overall mesh seed of 3 mm is used whilst a mesh seed of 1 mm is used in the middle region, resulting in a total of 23400 elements in the mesh.

Boundary conditions

The reference points for the two supporting rolls are clamped in all degrees of freedom. The moving roll in the middle is clamped in all degrees of freedom except in the vertical (force/deflection) direction where a displacement is added. To prevent the conical shaft from going sideways and slide of the rolls, a point in the middle of the shaft is locked in that direction.

Material

Material properties are assigned using linear material properties, with engineering constants obtained from SICOMP’s experimental data. The material is applied to the geometry with Composite Layups.

Steps

Nonlinear geometry is used in the calculations. The length of the time period is 1 and the initial increment size 0.05, to minimize the risk of instability of the simulation for different setups.

4.4.3 Method to evaluate results

First it is determined whether or not a scaling factor is necessary, by simulating the 1 mm thick pure TeXtreme-100 shaft and comparing the results to the test data. The scaling factor, S_F , is set as the ratio between the test deflection and the simulation deflection. The stiffness obtained from the simulation of the shaft proved to be greater than the one determined experimentally, i.e. with the three point deflection test. The difference is significant and therefore two procedures are used to assess the risk of failure of the shaft; one using the values gained from the simulations without any scaling factor, and one with scaled deflection and strain values. Meaning that for the first case, the deflection should be 26 mm, whilst for the second case a deflection of $\frac{26}{S_F}$ mm is accepted.

After the scaling factor is determined, various layups are simulated to determine if there are any that meet the stiffness demand. The stiffness is evaluated by using the displacement-reaction force graph of the reference point of the moving roll. An example of a displacement-reaction force plot is shown in Figure 4.3. From the plot, the displacement, corresponding to 300 N applied force, is saved. The curve is assumed to be linear, therefore interpolation is used when no time step point lands on 300 N.

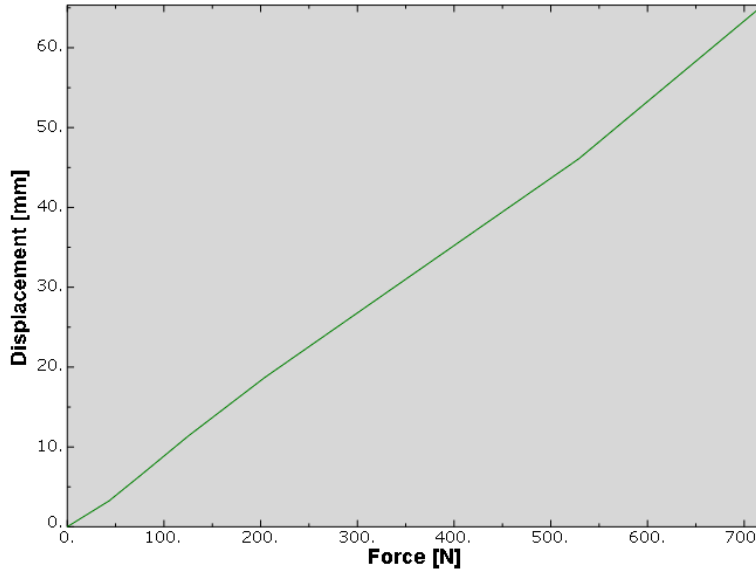


Figure 4.3: *Displacement-Reaction force relation for the moving roll.*

The layups that fulfil the stiffness demands, are further investigated with respect to strength. The strength is evaluated in each ply of the layup. Each layer's maximum and minimum true strain value, in both the in-plane directions and the shear direction, are compared to material strength data from SICOMP material test, see Appendix C. For the second case, the strains are scaled and then compared to the SICOMP data.

5 Results and Discussion

In this chapter the findings of the project will be presented and discussed.

5.1 Measuring results

The actual dimensions determined for the TeXtreme-100 fabric are confidential and presented in the confidential Appendix D.

However, it can be said that the fabric proved to have some inequality in the warp and the weft direction. Namely, the TeXtreme-100 fabric is less closed-packed in the weft direction than in the warp direction, resulting in an unbalanced weave. The reason for the wider tapes and the higher spacing in the weft direction depends most likely on the weaving process and loom, seeing that the same tapes are used in both warp and weft directions. The difference is about 6%. This unbalance results in a higher Young's modulus in the warp direction. These differences were not taken into consideration during the experimental tests on the material at SICOMP. Thus, providing only one stiffness for both the directions. This experimental stiffness can be either the warp, the weft or a mixed stiffness value. It is unknown due to insufficient stack-up information, i.e. that it is not known if the layup is created in a manner so that the warp/weft direction is the same in every layer or not.

The determination of the yarn thickness was not as straightforward as the determination of the yarn width and the yarn spacing. The mean thickness of one ply consists of both the warp and the weft yarn. If simply dividing the calculated value into two, the warp and the weft will not have the same fibre volume fraction (because the cross section areas would not be the same). Therefore the method described in Section 3.1 is used, resulting in the same fibre volume fraction in both strands. In other words, it is assumed that the wider yarn (the weft yarn) becomes more compressed than the warp yarn when weaving, rather than assuming that the weft tape becomes loose and gaps arise lengthwise.

In Appendix D it can be seen that SICOMP's average ply thickness is approximately 2 % higher than the thickness computed using the microscope pictures. A plausible explanation for this is the extra matrix at the laminate surface top and bottom, used for a smoother finish. Therefore the calculations in the software for the RVE were based on the the lower value of these two. The ply thickness for the floorball shaft on the other hand, was set as an mean value of both, assuming that it has a little extra matrix at the surface.

Worth mentioning again is that the measurements were performed on dry fabrics. The fact that the fibres/strands might move, spread and even change their shape when being impregnated with the matrix during manufacturing processes, should not be neglected. This could result in slightly different warp and weft width and spacing in the finished product, than the ones obtained for dry fabrics.

5.2 Strand properties and engineering constants

The computed strand properties, and thereby the engineering constants used for the simulations, are confidential and presented in the confidential Appendix D. The impregnated yarn properties were both computed using the Rule of mixtures and Halpin and Tsai method in MATLAB and taken directly from the software FETex. When comparing the results, there were no differences obtained for the longitudinal stiffness and the major Poisson's ratio, indicating that the program also used the Rule of mixtures. The results for the transversal stiffness and the in-plane shear, on the other hand, differ from each other significantly. This is because FETex calculates these properties using *Chamis method*. The method was not studied, but interested readers are referred to [38], whilst the more familiar method, Halpin and Tsai, is used to calculate the properties by hand (MATLAB). This difference in transverse direction of the strands, proved to be negligible for the material properties of the weave.

By changing the fibre stiffness in longitudinal and transversal direction, but maintaining all other yarn parameters constant, difference impregnated yarn properties are observed in FETex. These values are presented in Table 5.1 and Table 5.2, together with the corresponding material properties of the fabric, from TexComp. In Table 5.1 it can be seen that a ten times (900 % difference) higher transversal stiffness (from 25 GPa to

250 GPa) results in less than 10 % difference in all weave properties. Table 5.2 shows that 20 % difference in longitudinal stiffness also leads to very little change in the shear modulus and out-of plane Young's modulus. On the other hand, the influence on the in-plane stiffnesses is not negligible, approximately 20 % difference in the warp and weft (11 and 22) stiffness directions.

Table 5.1: The influence of the strand's transversal stiffness on the stiffness and shear of the weave. The last row represents a percentual difference. Units for stiffness and shear are given in GPa.

Impregnated yarn						Weave					
Longitudinal			Transversal			Young's modulus			Shear modulus		
E	G	ν	E	G	ν	E ₁₁	E ₂₂	E ₃₃	G ₁₃	G ₂₃	G ₁₂
250	22	0.3	25	10	0.3	72.558	68.881	2.876	0.911	0.892	2.290
250	96	0.3	250	96	0.3	73.104	71.153	3.050	0.946	0.925	2.620
0	336	0	900	860	0	0.75	3.3	6.05	3.84	3.7	14.41

Table 5.2: The influence of the strand's longitudinal stiffness on the stiffness and shear of the weave. The last row represents a percentual difference. Units for stiffness and shear are given in GPa.

Impregnated yarn						Weave					
Longitudinal			Transversal			Young's modulus			Shear modulus		
E	G	ν	E	G	ν	E ₁₁	E ₂₂	E ₃₃	G ₁₃	G ₂₃	G ₁₂
250	22	0.3	25	10	0.3	72.558	68.881	2.876	0.911	0.892	2.290
200	21	0.3	25	10	0.3	58.513	55.792	2.868	0.907	0.888	2.278
20	4.55	0	0	0	0	19.36	19	0.28	0.44	0.45	0.52

Thus, the difference between the transverse stiffnesses from the two methods should not have a major impact on the final result. The engineering constants for the RVE in ABAQUS CAE, are determined using the results from FETex. This due to the possibility to make small adjustments and obtain new results quickly.

5.3 Software usage

The numerical values of the material properties obtained using the different approaches are found in Appendix D. In Table 5.3 on the other hand, the difference between the software results and the experimental data from SICOMP, are presented.

Table 5.3: Procentual difference of stiffness and shear between software results and experimental ones.

	E ₁ (warp) [%]	E ₂ (weft) [%]	G ₁₂ [%]
SICOMP	X		X
WiseTex/TexComp	11	4	-11
ABAQUS RF	23	16	-
ABAQUS/MATLAB	24	16	-

It can be seen that all the approaches used, predict a stiffer material compared to the results from the experimental test performed at SICOMP. This is realistic, considering that a perfect material, i.e. no defects in the fabric, is assumed for the models. The material used at SICOMP, on the other hand, went through a couple of manufacturing stages. Manufacturing of the fibres, the binder, the yarn, the strand, the composite and the final part, all these stages can conduct to imperfections in the fabric making the material less stiff.

This is however not the only error source for the differences. In the subsections below, the issues with each program and how that influences the final result are discussed.

5.3.1 WiseTex

The method using WiseTex for building the RVE and determining the material properties in TexComp, proved to be the fastest way for evaluating the elastic properties of a fabric.

As mentioned, in WiseTex the user can be very specific and detailed when creating a unit cell. Apart from the parameters that have to be set, the user can choose to define even more profound yarn properties, such as compression, bending, tension and friction parameters. Adding a compression factor to a yarn means that the yarn thickness will shrink and the width will grow when weaving the fabric. Compression was added to study the influence. It showed that adding compression had a minor influence on the result when analysing TeXtreme but a rather big influence on fabrics with more elliptical or circular cross section shape. This makes sense, giving that it should be difficult to compress something as flat as TeXtreme even further. The other optional parameters were not investigated, for it extends beyond the scope of this work.

The influence of the mandatory parameters, that have to be set to be able to build a unit cell, were all closer looked into. This because depending on which data sheet is used, various fibre mechanical properties can be found. The parameters that have little or no influence on the final stiffness and shear result obtained in TexComp are:

- fibre Poisson's ratio - which only influences the final Poisson's ratio of the fabric, not the stiffness and shear noticeably, and
- fibre friction coefficient - which has no influence on the final result at all.

The fibre density, linear density and fibre amount are related to each other according to

$$\rho_l = \frac{\pi}{4} d_f^2 \rho \quad (5.1)$$

where ρ_l is the fibre linear density, d_f the fibre diameter and ρ the fibre density. When changing one of these, the software automatically recalculates one of the other two (users choice). When modifying all the quantities approximately 2 % the final results also differed around the same amount. However, no real conclusion could be made. When instead, keeping the fibre density constant and changing the two others significantly (over 100 %) the same values were always observed. This can be explained by looking deeper into the fibre volume fraction equation 2.1 for a strand

$$V_{f,strand} = \frac{a_{cs} N}{A_{cs}} \quad (5.2)$$

where

$$a_{cs} = \pi \left(\frac{d_f}{2} \right)^2 \quad (5.3)$$

$$N = \frac{\rho_{l,s}}{\rho_l} \quad (5.4)$$

$$A_{cs} = \pi \left(\frac{d_s}{2} \right) \left(\frac{t_s}{2} \right) \quad (5.5)$$

where $\rho_{l,s}$ is the linear density of the strand, d_s is the strand width and t_s the thickness (seen as an ellipse). With equation (5.3), (5.4) and (5.6) inserted in (5.2) the fibre volume fraction reads

$$V_{f,strand} = \frac{4\rho_{l,s}}{\pi\rho d_s t_s} \quad (5.6)$$

It becomes clear which parameters influence the strands fibre volume fraction and thereby the final result. Studying the influence of the yarn linear density it was found that it nearly has a linear influence on the stiffness and out-of-plane shear, but a somewhat higher influence on the in-plane shear.

Parameters that could be modified for the weave are yarn spacing and crimp. As mentioned in Section 2.3 the crimp is significantly lower for the TeXtreme material than traditional weaves. Thus, it was no

surprise that no major result changes in the result are observed when changing the crimp parameter. The spacing on the other hand, contributes substantially to the final result. It is clear that a sparsely packed weave has more room for the matrix, leading to a lower total fibre volume fraction and thereby a weaker material.

A good feature in WiseTex is the warning message that informs the user in case of too small spacing values, i.e. the fabric is build to tight, and thereby preventing “lengthwise” penetration. Unfortunately, the feature is not evolved to prevent “through thickness” penetration, making it possible for the top of one strand to penetrate the bottom of another. This is the main reason why the fabric can not be used for exporting to ABAQUS CAE for RVE stiffness study. The geometry can be exported without problem, however but the strands can not be recognised as individual parts when meshing the RVE.

It seems that the developers are aware of this problem and have therefore implemented the strand shrinking option in FETex. Unfortunately, this could not be used since FETex has limitations for what geometries could be exported and has problems with exporting yarns, matrix and meshes. Another reason for not using this feature is that FETex writes a script for ANSYS Classic and it is preferred to use a more up-to-date software to build a FEM model in. Tests were performed with importing the files to ANSYS Classic, which was time consuming and when trying to read specific model files problems and errors occurred. The other feature in FETex, calculating impregnated yarn properties, on the other hand, was used extensively.

In TexComp it was found that all four solvers return similar material properties for the TeXtreme-100 model. The Mori-Tanaka solver was used because it is the default setting and the fastest one.

5.4 TexGen

The main advantage with this program is the ability to define a gap between the yarns, and thereby escape the penetration problem observed using WiseTex. Another plus is that the program is easy to use and only the elementary parameters (such as yarn width and thickness, and weave type) have to be set. The programs weakness is related to its simplicity, meaning that an unbalanced weave can not be created (with different weft and warp geometry), the user can not predefine the crimp and an external FEM solver must be used to obtain results. The fact that a numerical solver has to be used results in significantly longer computational time compared to WiseTex. Another drawback is the programs auto-adjust feature. Trying to create the extreme geometry relation ($\sim 200 : 1$) the program automatically changes the values to gain a smaller aspect ratio. This is the main reason for not recommending the program for TeXtreme fabrics.

5.5 ABAQUS CAE

In this subchapter the results for the three geometries created in ABAQUS CAE are presented.

5.5.1 Simple box

Worth mentioning is that the shape of the box was intended to be cuboid with different lengths on all sides, to ease the recognition of the rotation and deformation of the box. This proved to be a unfitting choice, since the box needs to have a square shape seen from the top, so that the last case needed to determine the full $[ABD]$ -matrix can be run. This criteria is not addresses in Karkkainen’s paper. For only determining the $[A]$ -matrix, on the other hand, it is not necessary to use a square shape, since only the three first cases are needed for the Young’s modulus evaluation. When using the latter geometry, both with the reaction force method and the MATLAB script good results were obtained, compared to the engineering constants, that are used as a reference, see Table 5.4.

These findings indicate that the two methods (RF-method and $[ABD]$ -matrix method) give quite reliable results for a simple box.

The simple box model has been solved with and without running the PYTHON script, i.e. with and without the implementation of periodic boundary conditions. There was no significant difference observed for the two cases, this most likely because small strain and curvature (0.01-0.1) are used.

Table 5.4: Material Properties for the simple box, using ABAQUS RF and the MATLAB script.

	Case 1 (E_1) [GPa]	Case 2 (E_2) [GPa]	Case 3 (G_{12}) [GPa]
Material properties	50	50	3.5
ABAQUS RF	49.6	49.6	-
ABAQUS/MATLAB	50.1	50.1	3.5

5.5.2 Unidirectional composite

This geometry was chosen not to have the same side lengths and therefore only the $[A]$ matrix is obtained instead of the full $[ABD]$ matrix. The results from the ABAQUS model are compared to other methods since no test data was available for the specific composite. The composite was built in WiseTex and the stiffness evaluated in TexComp. Also, simple hand calculations (rule of mixtures and Halpin-Tsai) were used to determine the stiffness. The stiffness results obtained in ABAQUS, both using the reaction force method and with the MATLAB script, correlate well to the results from the other methods, see Table 5.5. This proves that the methods also work for simple composites, using different lengths on all sides.

Table 5.5: Material Properties for the unidirectional composite, using WiseTex, Rule of mixtures, ABAQUS RF and the MATLAB script.

	Case 1 (E_1) [GPa]	Case 2 (E_2) [GPa]	Case 3 (G_{12}) [GPa]
RoM/Halpin-Tsai	121.2	12.4	-
WiseTex	127.2	9.8	3.8
ABAQUS RF	119.6	11	-
ABAQUS/MATLAB	126.6	11.6	4.1

5.5.3 TeXtreme model

The geometry for the TeXtreme model was built inside ABAQUS CAE using the dimensions determined from the measurements on the TeXtreme fabric. The major difference with this model compared to the other tested ones was the extreme dimensions of the material (~ 20 mm and 0.1 mm). One problem that occurred because of this was the bad mesh quality, because of the high aspect ratio of the elements. Approaches to improve the quality were made by changing the element types and creating partitions with lower seed, i.e. critical regions with smaller element. Convergence was found around 3.5 million elements. Decreasing the seed further (increasing amount of elements over 3.5 million), and thereby slightly decreasing the aspect ratio, improved the result negligibly.

The bad mesh quality is probably one of the reasons for the bad correlation between the ABAQUS methods (reaction force method and MATLAB script) and the experimental data, obtained in Table 5.3.

Other reasons for the bad results may be the fact that no periodic boundary conditions were used, the size of the RVE is set as a single unit cell and the fact that the crimp was neglected when using global orientation is an error source, since that leads to a stiffer material.

5.6 Floorball shaft

The simulation of a shaft undergoing the three point deflection test can be seen in Figure 5.1.



Figure 5.1: ABAQUS CAE simulation of a deformed shape of a floorball shaft.

The presented method for simulating the shaft seems to work and could be a helpful tool when developing new shafts. However, for results closer to the experimental ones, more precise input data is a necessity. With better knowledge of the material properties, less assumptions would be needed and it might be possible to avoid the need of a scaling factor.

Further, a better calibration of the simulation could probably be performed if experimental data from more than one shaft could be used. This is since, out of the tested shafts, only one is made purely out of TeXtreme-100, which is the only material with known material properties for both stiffness and strength.

Results obtained from the simulations while investigating different layups for the shaft are presented in Appendix A. The obtained stiffness data of the simulations are saved in a table and used for tuning of the stiffness of the shaft for different layups. Previous simulations are used to estimate an approximate the layup for the next shaft. The process was performed manually.

A convergence study was performed to determine the mesh size needed for the shaft, the result is presented in Figure 5.2. The chosen mesh contained 23400 elements with a local seed of 1mm in the middle of the part and an overall seed of 3mm. The simulation time was approximately 4 minutes.

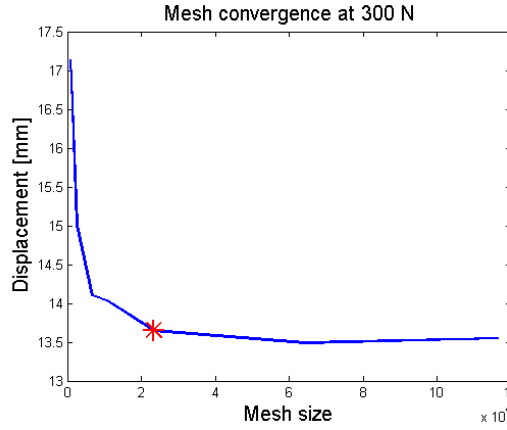


Figure 5.2: *Mesh convergence. Red star is the mesh size chosen.*

The simulations indicate that it is not possible to design a shaft that fulfils the rigidity requirements for the current shapes using TeXtreme-100 fabric. All versions of layups failed at least one strength criteria, since the true strains L_{11} , L_{22} or L_{12} were larger than the strength values obtained from the SICOMP test. The method used for determining the strength is conservative since a linear material model is used and the strength criteria is derived from the test data.

The simulation model in ABAQUS CAE has been developed and optimized to be as valid as possible, still there are great differences between the results from the model and the ones from the three-point-test. Errors sources lie mainly in the uncertainties around the part leading to the use of simplifications and assumptions when creating the model. Some uncertainties that are considered to influence the result more than others are:

- The geometry of the simulated reference shaft differs from the tested one.
- Material properties: the matrix was unknown, the quality after manufacturing, the impact from defects.
- Manufacturing quality with the crimp tape and oven compared to autoclave, the curing process is unknown, the impact from hand layup.
- Material layup and directions: thickness per ply, directions for weft and warp, overlapping of different layers, influence from slightly angled fibres (occurring when the fabric is rolled on a cone shape).
- Only one shaft was used to calibrate the scaled values.

6 Conclusions

It is important to know how close the actual dimensions of the material are to the nominal ones used in the modelling methods. Because in the methods used, the material dimensions are a key factor for obtaining reliable results of the mechanical elastic properties. The nominal dimensions given for TeXtreme-100 by OXEON should only be used as an estimation. TeXtreme is not a fully balanced fabric and the difference in stiffness for warp and weft directions is approximately 6% according to simulations with the measured fabric dimensions. These effects should be considered if small safety factors are the case.

All modelling methods used, gave higher elastic properties for the material compared to experimental test data, due to no imperfections in the fabrics are considered.

WiseTex/TeXComp proved to be a good method for determining mechanical elastic properties for the TeXtreme material. The material properties can be assigned and controlled with a high level of detail. The processing time is short compared to other methods. The software family is currently in a beta stage and contains several bugs. Solving these would improve the quality of the programs, increase its range and prevent the user from building unrealistic composites.

It was found that the parameters with the largest influence on the final material properties are the ones in that determine the fibre volume fraction of the fabric

$$V_f = V_{f,strand} = \frac{4\rho_{l,s}}{\pi\rho d_s t_s} \quad (6.1)$$

and therefore not knowing all the parameters, that can be set in WiseTex, will not affect the result highly.

TexGen is both easy to use and to understand. On the other hand, it is limited to simple geometries (i.e. balanced weaves and no possibility to modify crimp). An external FEM-solver is needed for the calculations and the processing time for this method is significantly longer than for WiseTex/TeXComp. TexGen is thereby not recommended for modelling TeXtreme-100.

With the ABAQUS CAE methods, reliable results for simple cases and geometries can be obtained, using both the reaction forces or the MATLAB script. The extreme dimension ratio for TeXtreme-100 required a large amount of elements to resolve the geometries. This resulted in a heavy model with bad element aspect ratios. The results obtained for TeXtreme-100 was even stiffer than the ones obtained from WiseTex. The total processing time using this method was significantly longer than using WiseTex. It would be preferable to use another pre-processor than ABAQUS CAE to control the geometry and meshing in a better way.

The model used for simulation of the floorball shaft had poor correlation to the manufactured and experimentally tested shaft. The model built in ABAQUS CAE is stable and returns the same results when using different approaches for building the geometry, e.g. using volume elements or shell elements. Therefore, the reason for the significant difference probably lies in the insufficient knowledge about the material, i.e. how the shaft is manufactured and what quality it has. All layups with the TeXtreme-100 material failed the strength criteria set by the true strains obtained from SICOMP test. The strength criteria used is conservative and should be revised to better fit the strength requirements from IFF. In conclusion, it will be challenging to design a shaft using only TeXtreme-100.

7 Future work

Recommendation for future work regarding the modelling of the TeXtreme-100 material with a FEM-solver, is to use a different pre-processing program, one more suited for meshing complicated shapes, e.g. ANSA. This alternative software might lead to a lower element aspect ratio. Further, if the mesh can be controlled to have the same amount of elements on opposite sides, the periodic boundary script can be used. Another approach could be to model an larger RVE and thereby depart from the influence of the boundary conditions.

WiseTex is a well suited software for this kind of composite material studies, and it is recommended to keep using the program, especially if the bugs are resolved.

In this thesis the main focus lies on the stiffness evaluation. It would be of interest to develop the methodologies further so that the material strength could be predicted.

A recommendation for further experimental study is to, if possible, perform experimental tests on the material, with known warp and weft direction, so that different stiffness can be obtained for the two yarn types. Yarn width and spacing measurements on final products could also provide more accurate values than measurements on dry fabrics.

Regarding the floorball shaft it is strongly recommended to investigate why there was so poor correlation between the simulated test shaft and the actual tested one. The model built so far is a good starting point for further development. An optimisation and automation of the process would be good to perform. By adding a more automated workflow including for example a script that makes all the post processing and delivers the results would speed up the simulation process. Even more beneficial would be to perform an optimisation where important parameters could be iterated to find the best solution. It is recommended to investigate how a mixture of TeXtreme and other materials could affect the performance of the shaft. One idea is to use a material, that can withstand the deformation better, as an outer layer of the layup to keep the microcracks on the TeXtreme inside.

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A Floorball shaft

Mechanical properties for different layups of TeXtreme-100 fabric are presented in the following tables. In the first table the scaled results with scale factor of 1.5 are presented, whilst in the second table the non-scaled results, are presented.

The stiffness values in the tables are presented as how much displacement the middle roll experienced while 300 N of force was applied. The strength is presented for the three true strains L_{11} , L_{22} and L_{12} . For each one of them are the obtained values for both tension and compression compared against SICOMP test data.

Layup [<i>direction * n - plies</i>]	Stiffness		Strength		Number of plies
	Displacement at 300N [mm]	Scaled displacement at 300N [mm]	$L_{11} = L_{22}$ [e-3] allowed [18 -7.2] e-3	L_{12} [e-3] allowed [18] e-3	
0*10p, Reference shaft	13.6	20.5			10
0*8p	17.6	26.3	-	-	8
0*6p , 45*4p	17.4	26.0	-	-	10
30+*3p , 0*4p , 30-*3p	17.9	26.8	18 , -23 = 8 , -15	30 , -21	10
30+*5p , 0*2p , 30-*5p	17.6	26.4	27 , -27 = 9 , -8	32 , -24	12
30+*5p , 0*2p , 30+*5p	17.2	25.9	-	-	12
30+*7p , 30-*7p	18.0	26.9	12 , -14 = 4 , -4	33 , 27	14
30+*14p	17.1	25.7	12 , -18 = 6 , -7	30 , 30	14
45*24p	17.7	26.6	3 , -8 = 3 , -8	39 , 39	24

Layup [<i>direction * n - plies</i>]	Stiffness	Strength		Number of plies
	Displacement at 300N [mm]	$L_{11} = L_{22}$ [e-3] allowed [18 -7.2] e-3	L_{12} [e-3] allowed [18] e-3	
0*3p , 45*5p	26.8	12, -13 = 7.9, -12	18.4, -18.7	8
25+*8p	25.0	-	-	8
40+*14p	27.4	4, -7 = 3, -4	24, -24	14
45*16p	26.5	2.4, -5.4 = 2.4, -5.4	26, -26	16

B Confidential Experimental test of TeXtreme floorball shafts

C Confidential SICOMP experimental test data

D Confidential TeXtreme

E WiseTex-ABAQUS

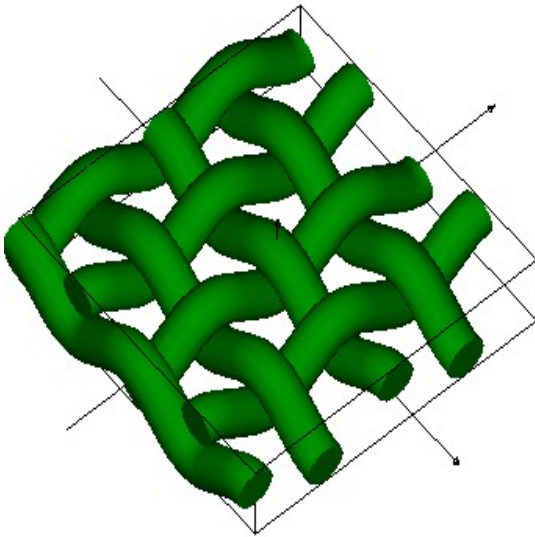
Step-by-step tutorial:

Creating a Plain weave Unit Cell in ABAQUS CAE

Using exported Fibre yarns from WiseTex

Save WiseTex fabric

The created plain weave presented below is built in WiseTex, and will be used for a demonstration on how to create a Unit cell in ABAQUS CAE.



Unit cell size:	16.0 x 16.0 x 4.0 mm
Areal density:	1714.6 g/sq.m
Porosity (inter-yarn):	55.1 %
Fibre volume fraction:	23.6 %

Filename:	Weave-Orthogonal4x4
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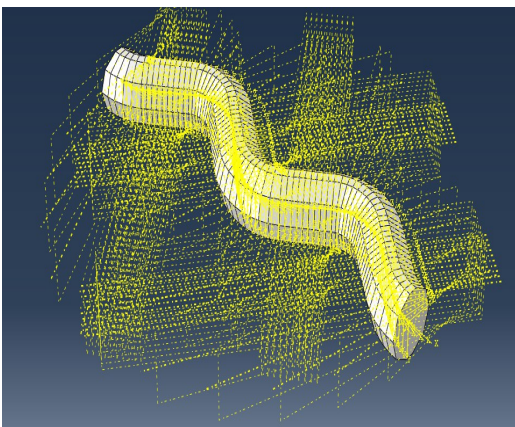
Save the geometry as an ascii file to be able to export it to ABAQUS CAE;
File=>Write ASCII file

Open the Python script that came with the WiseTex software: "WiseTex_to_Abaqus.py".

In the script change the pathname to your exported WiseTex file:
`myfile = open("C:\...\Weave-Orthogonal4x4.cfl")`

Build the yarns in Abacus:

Run the script in Abaqus



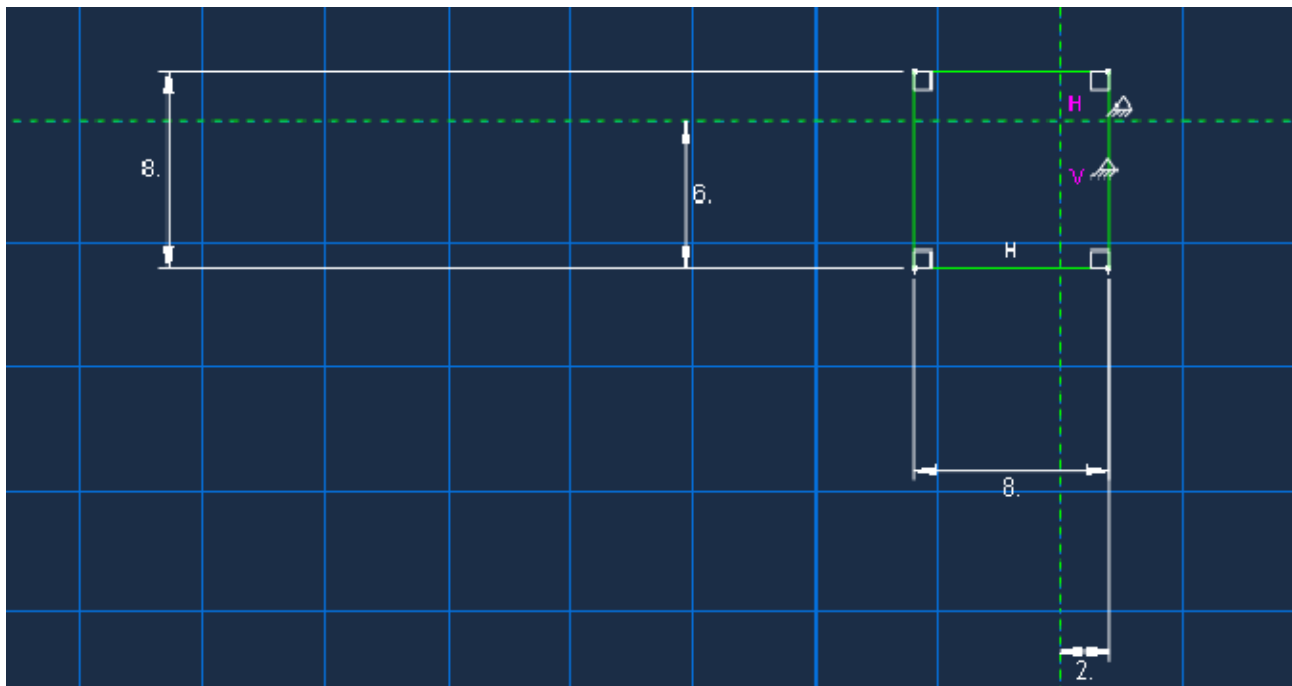
Hide Datum points, axis and planes etc.:

View => Part Display Options => Datum
Un-check all

Create matrix:

Create new Part "Matrix" (3D Modeling space, Deformable type, Solid Extrusion)

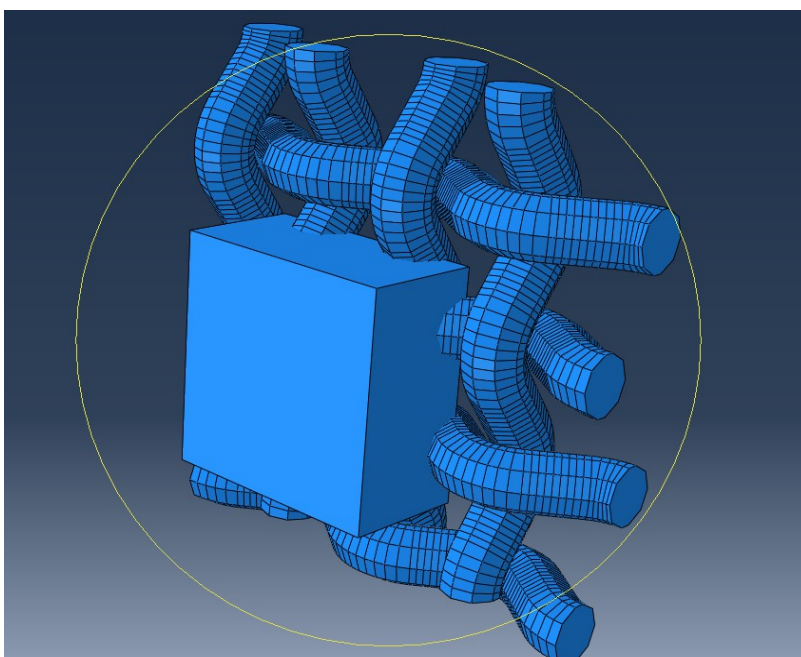
Create 2 construction lines (through origo) and set constraints so that the matrix ends up appropriate for the weave.



Finish sketch and extrude (4.2 mm)

Add matrix to assembly:

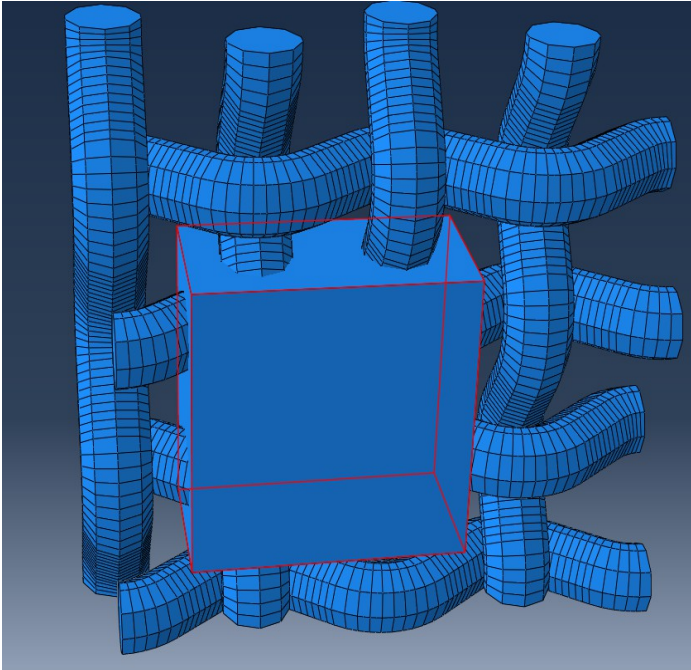
Double click on Instance under Assembly. Choose “Matrix” and Dependent (mesh on part).
(Normally you get the Yarns automatically in the Assembly Module under Instances when running the script, but in some cases you have to add it yourself together with the Matrix).



Translate position of matrix in assembly:

Press “Translate Instance” and choose the “Matrix”

Select a start point: [X,Y,Z: 0.0,0.0,0.0] and end point: [X,Y,Z:0.0,0.0,-2.1]



Remove matrix where the yarns will be:

Press “Merge/Cut Instance” and name the new Part “Matrixbox with holes”. Choose “Cut geometry” and “Suppress” Original Instance

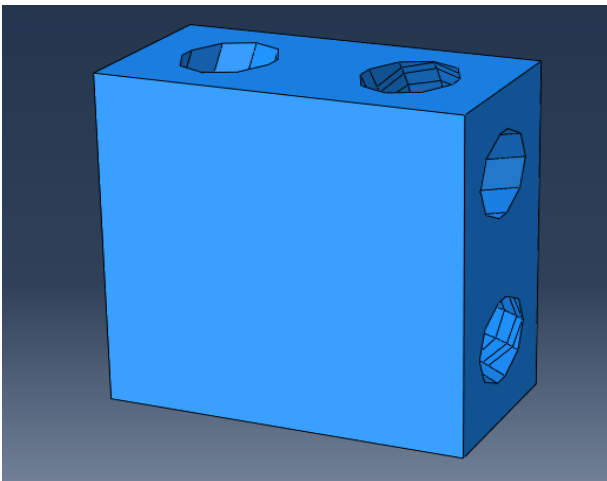
Select the instance to be cut:

choose the “Matrix”

Select the instance that will make the cut:

choose “I_Yarn_2”, “I_Yarn_3”, “I_Yarn_6” & “I_Yarn_7” (the ones that go through the Matrix) – (selecting all the yarn is also a possibility)

Suppress “I_Yarn_1”, “I_Yarn_4”, “I_Yarn_5” & “I_Yarn_8” if needed

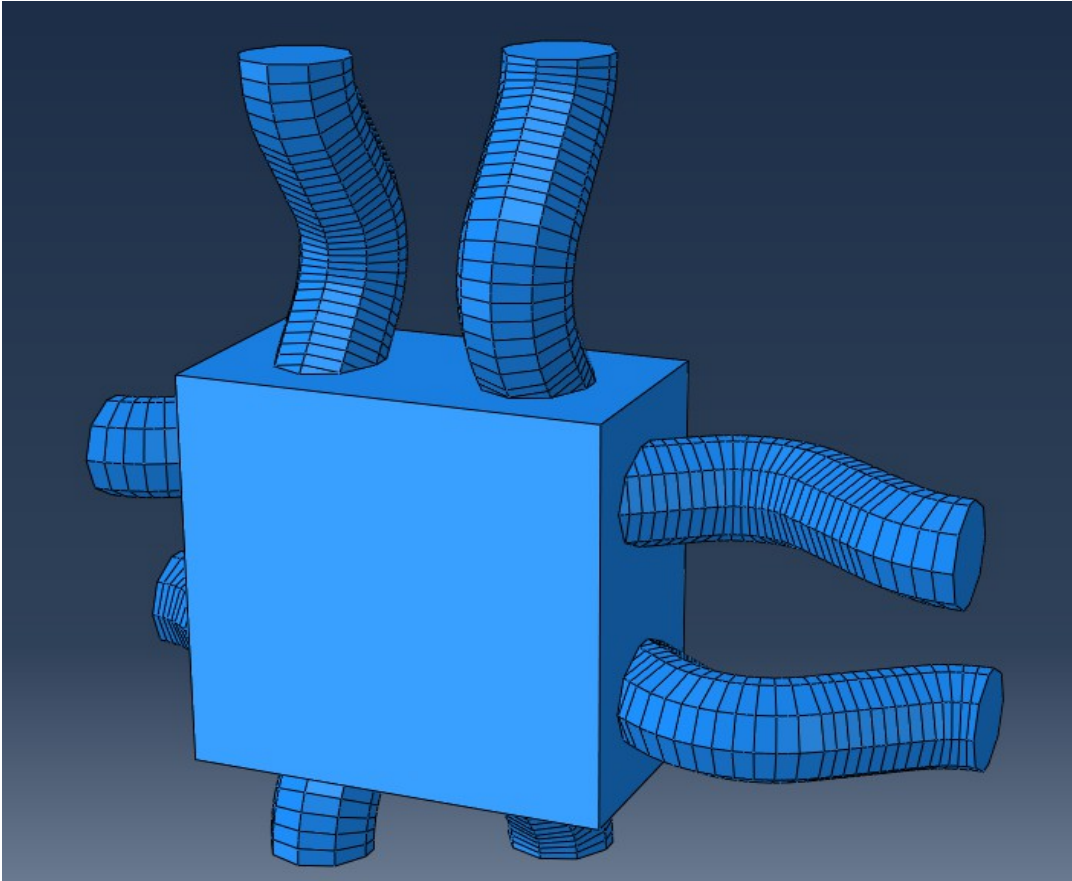


Resume the yarns: “I_Yarn_2”, “I_Yarn_3”, “I_Yarn_6” & “I_Yarn_7”

Create Plain weave Unit Cell (Matrix+Yarn part):

Press “Merge/Cut Instance” and name the new Part “Plain weave”. Choose “Merge Geometry”, “Suppress” Original Instance and “Retain” Intersecting Boundaries.

Select the instances to merge : select all visible (“I_Yarn_2”, “I_Yarn_3”, “I_Yarn_6”, “I_Yarn_7” and “Matrixbox with holes”)

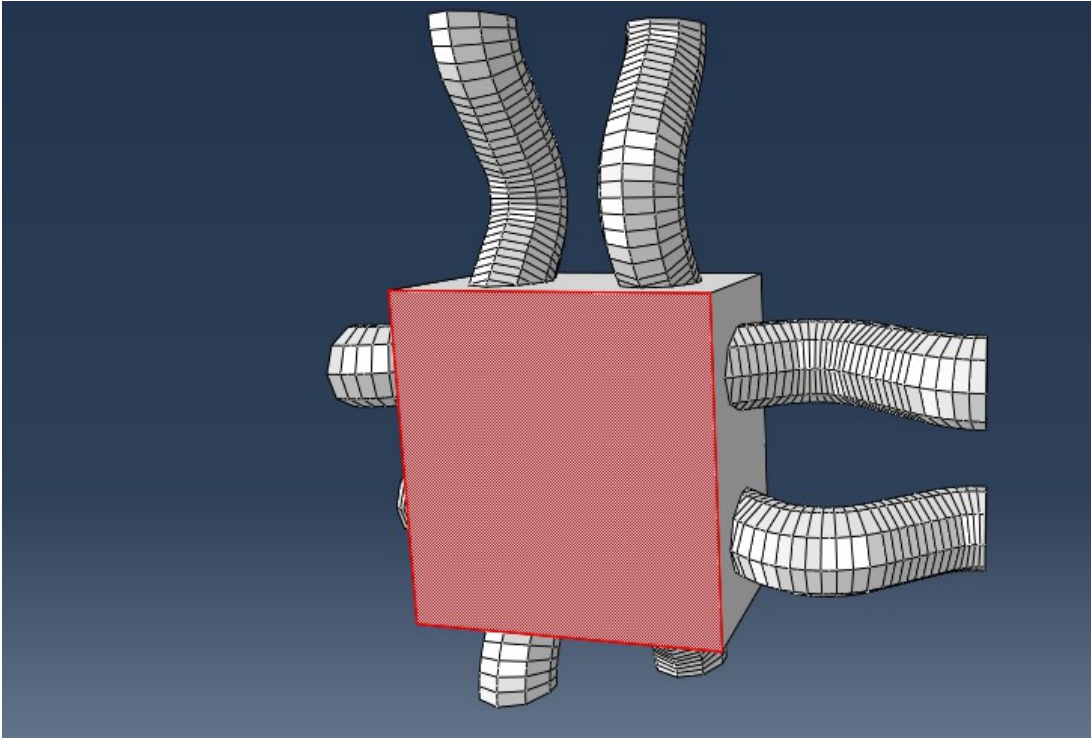


Cut of Yarns outside the Unit cell:

In Part Module; Choose “Create Cut: Extrude”

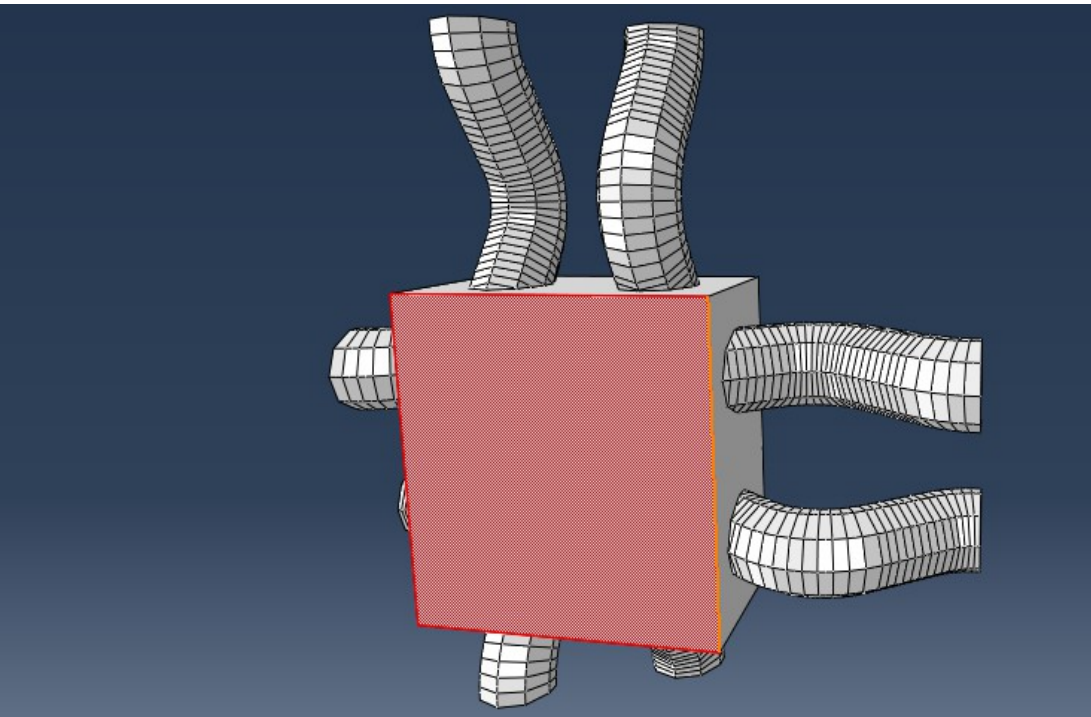
Select a plane for the extruded cut:

Select the top or bottom plane

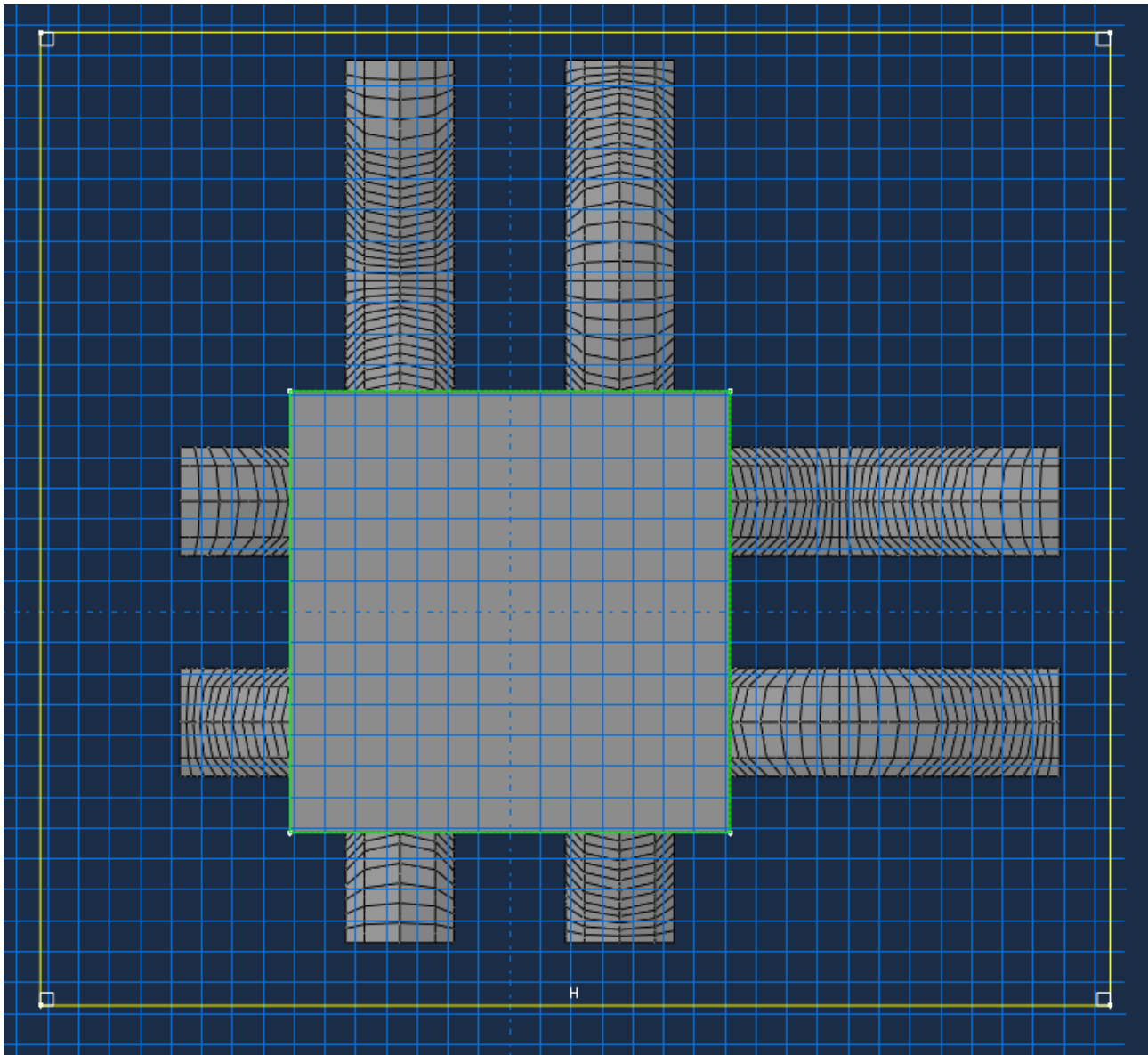


Select an edge or axis that will appear:

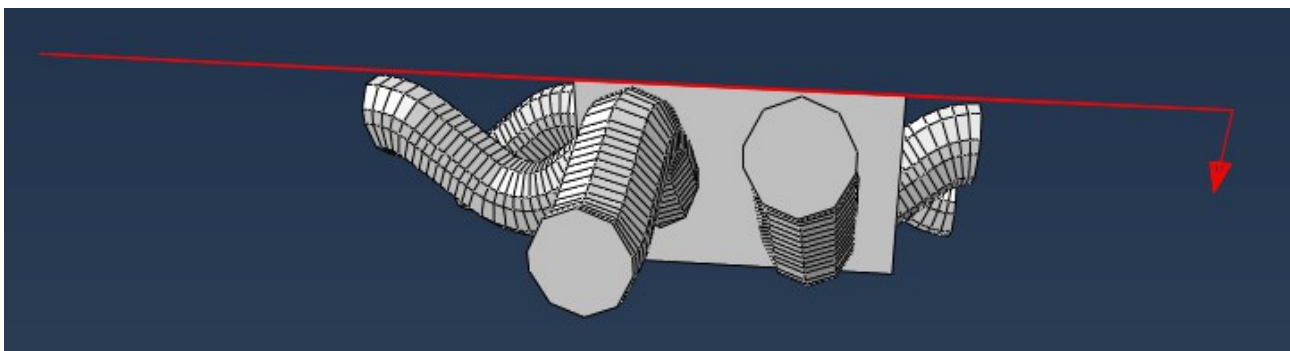
Select any edge in the plane



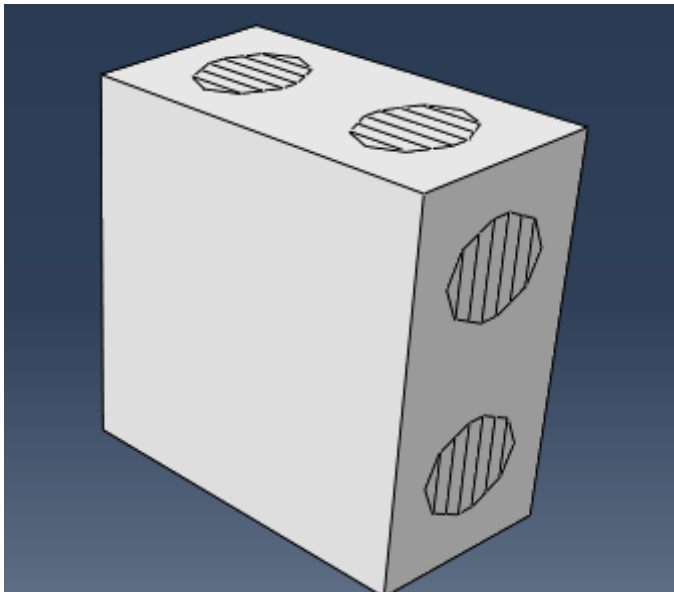
In the sketch section; Project the four edges of the matrixbox and Create a Rectangle that is bigger than the “Plain weave” Part and press Done



In the **Edit Cut Extrusion** dialog box choose the End condition type “Through All” and select the “Extrude direction” towards the Yarns



The “Plain weave” Part should look like this.



Matrix material:

In Property Module; Create a solid Homogeneous Section and name it “Matrix section”, press Continue => On the right side of the **Edit Section** dialog box, click on the “stress strain curve symbol” to create the Matrix material.

In the **Edit Material** dialog box name the new material “epoxy” and select Mechanical => Elasticity => Elastic.

Young's Modulus: 3300

Poisson's Ratio: 0.35

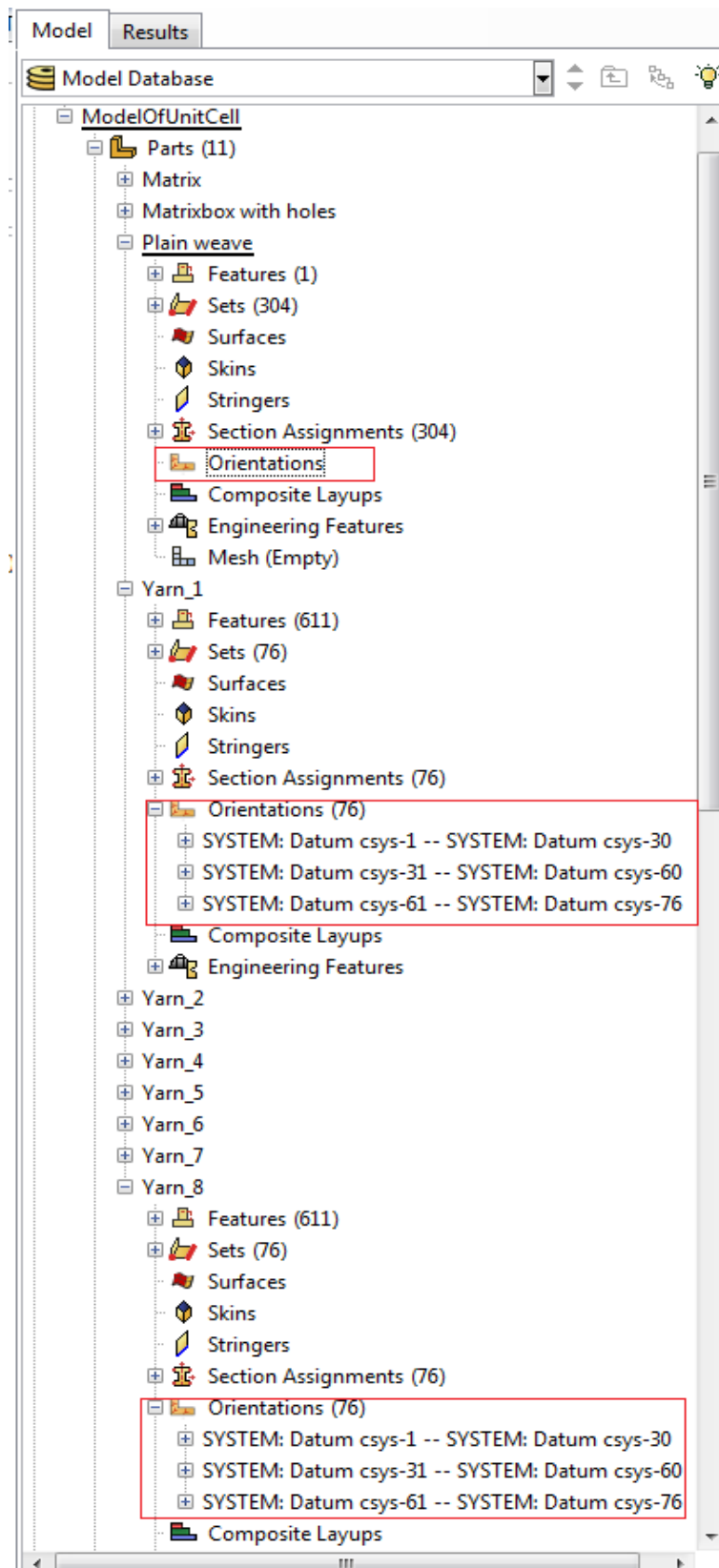
Click OK and select “epoxy” as the Material in the **Edit Section** dialog box. Click OK.


In the model tree under Parts under Plain weave double click on “Section Assignments” and Select the regions to be assigned a section: Choose the matrixbox

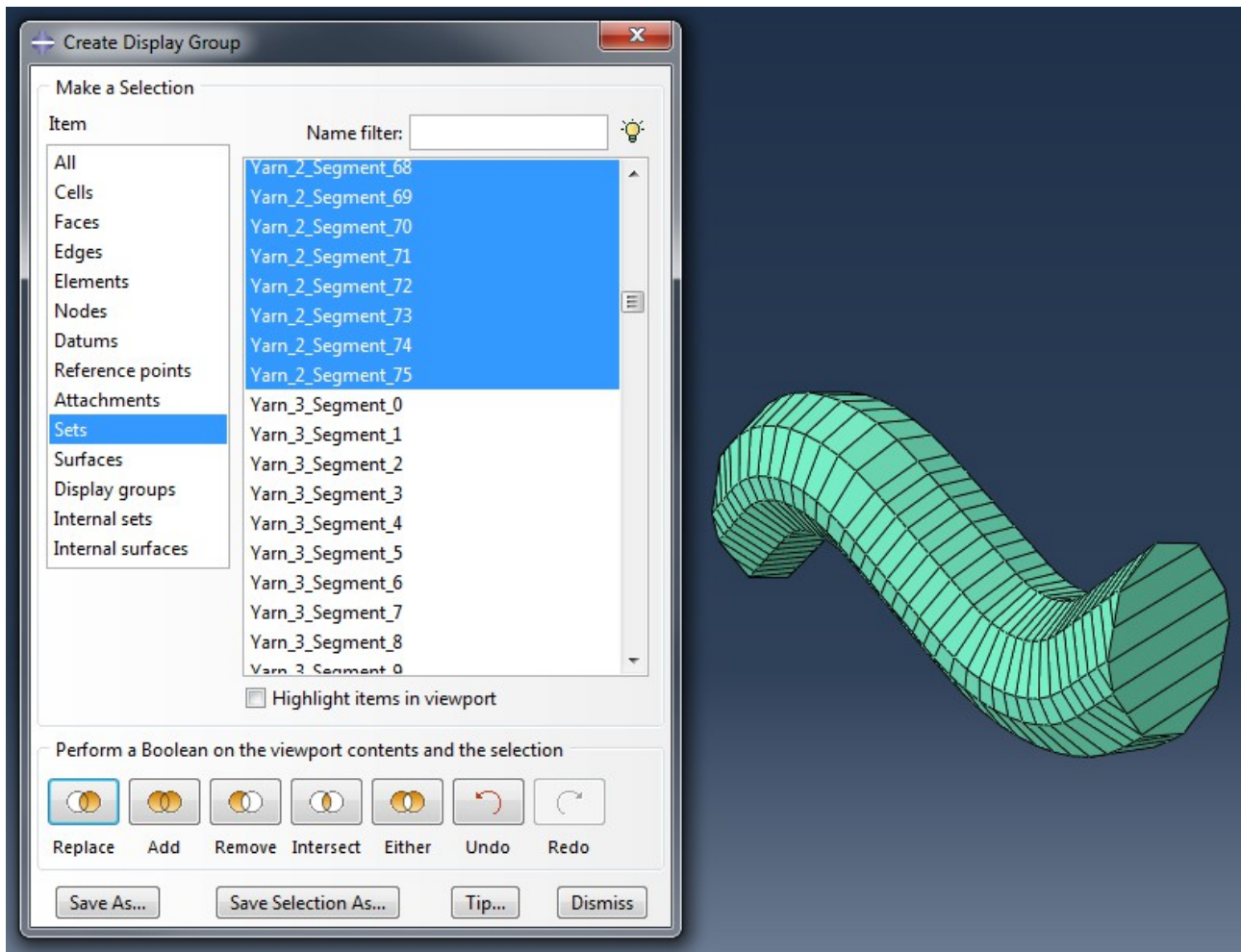
Click Done and the **Edit Section Assignment** dialog box appears, select “Matrix section” and click on OK.

Create Material Orientation for yarn:

We can see that we have Orientations (given from the WiseTex file) under Parts (11) for the Parts: “Yarn_1” – “Yarn_8” but not for the new merged Part “Plain weave”. (Merging e.g. two yarns together without the matrixbox also leads to no Orientation in the new merged Part).



Now use the “Create Display Group” symbol  in the “Toolbars” area to show one yarn at a time. Highlight all the Sets belonging to the same Yarn and press the “Replace” button:



Then press “Dismiss”.

In Property Module; Choose “Assign Material Orientation”

Select the region to be a local material orientation:

Select the whole visible Yarn

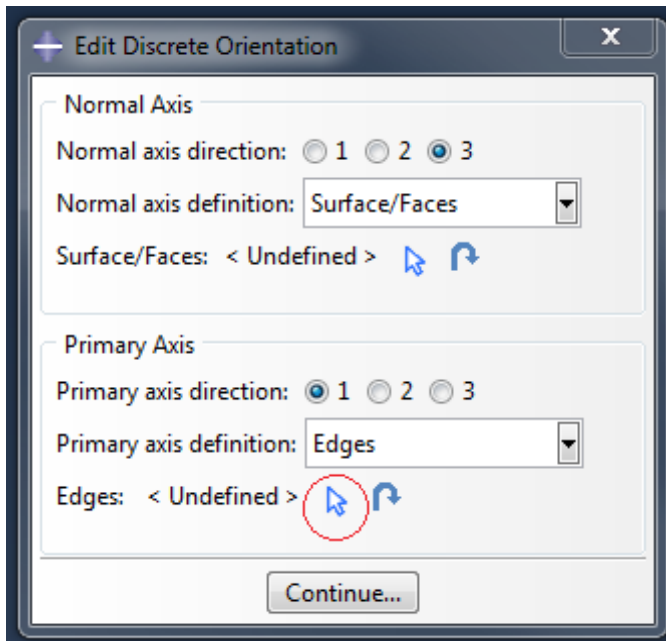
Press Done.

Select a CSYS:

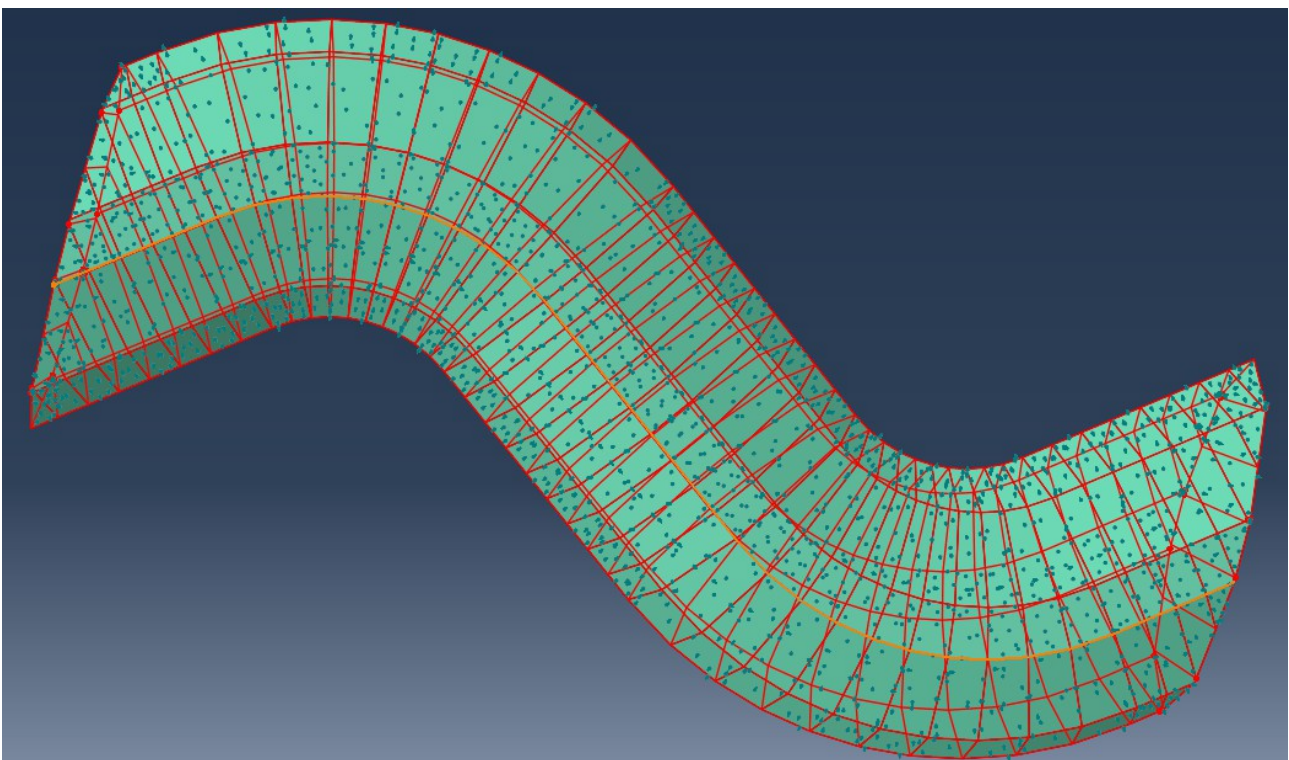
Press on the “Use Default Orientation or Other Method” button

In the **Edit Material Orientation** dialog box choose “Discrete” as the Orientation Definition and press on the pencil symbol that appears. The **Edit Discrete Orientation** dialog box appears

Press on the second mouse symbol



Select the regions that define the primary axis of the material orientation:
Change to “by edge angle” and choose 15.0, then select one of the mid lines:

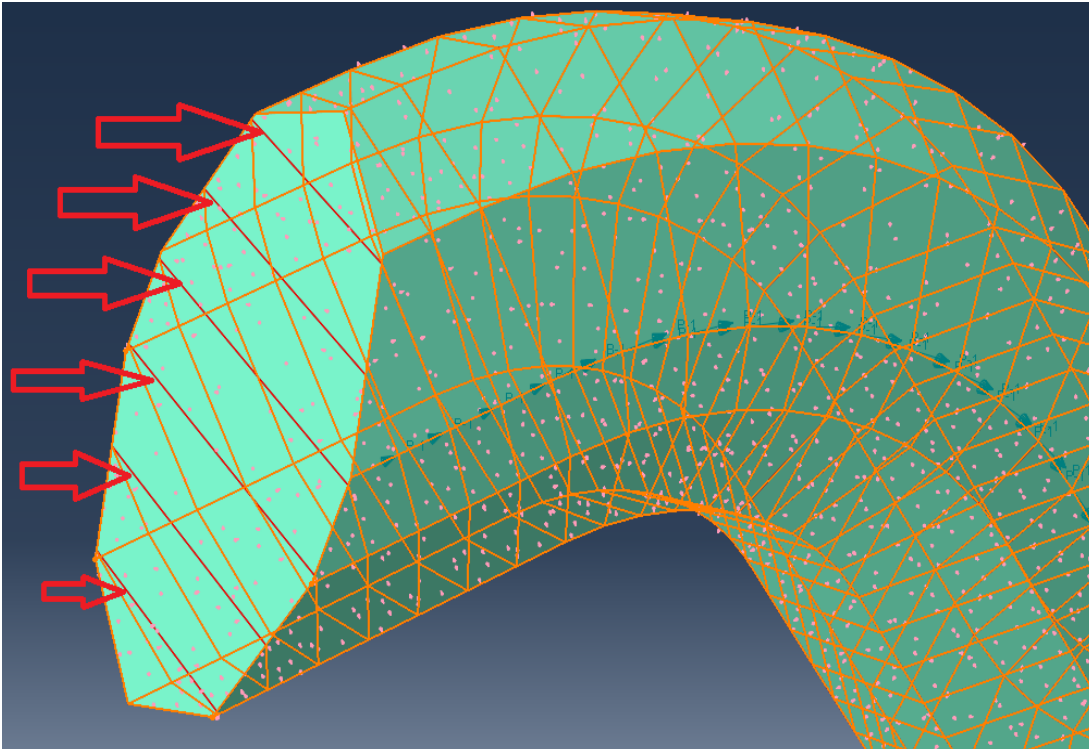


Press Done.

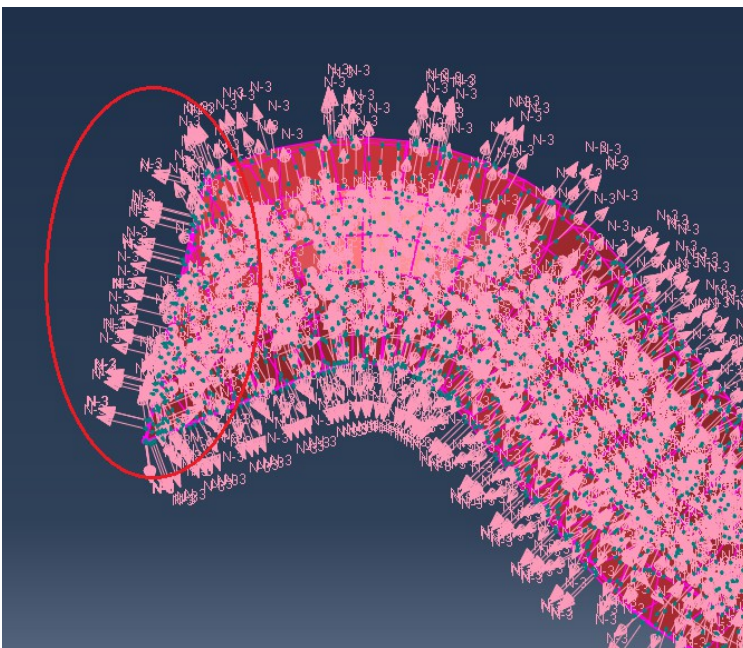
Then Press on the first mouse symbol in the **Edit Discrete Orientation** dialog box.

Select the regions that define the normal axis of the material orientation:

Keep “by angle” and choose 40.0, then for some reason one has to press the “Surfaces...” button and when the **Region Selection** dialog box appears press the “Dismiss” button (if you don't do this, sometimes you won't be able to select all the regions), then select the regions as shown below:

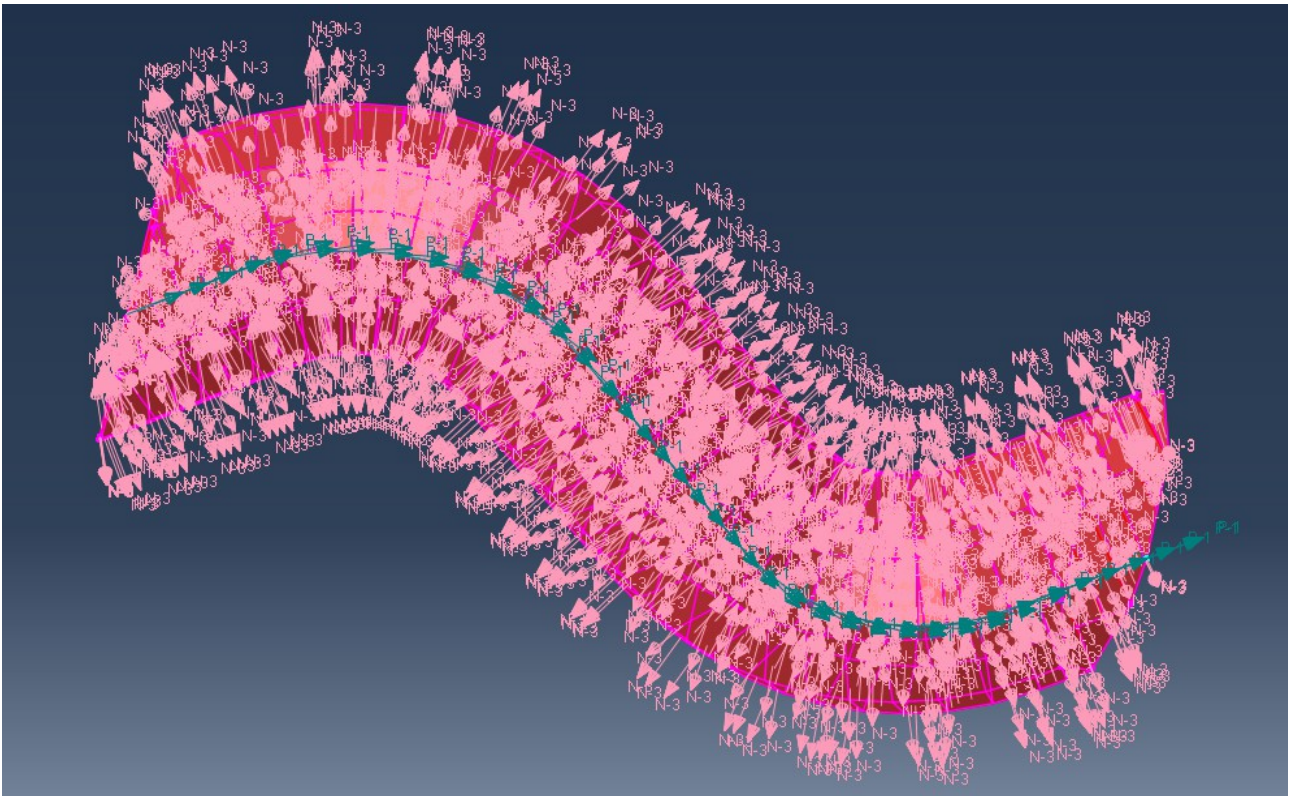


It is difficult to see, but some of the lines should remain unselected (red). If these lines are selected, i.e. turn orange (if you choose an angle of 90.0) then you will get some directions normal to the “Cut surface”:




which is not desirable. You will get Errors when you Submit a Job.

When choosing an angle of 40.0 on the other hand, it should look like this:



Click on the “Continue...” button when the **Edit Discrete Orientation** dialog box appears and “Cancel” when the **Edit Material Orientation** dialog box appears, click on YES in the next dialog box, Click on Done in the “Prompt area”

Repeat this for the remaining three Yarns.

Press the “Replace All” symbol  in the “Toolbars” area to show the whole Part again.

Create Step:

In the model tree double click on Steps (1); the **Create Step** dialog box appears.

Name the step "Loadstep". Select "General" as the **Procedure type**, and from the list of available General procedures, select "Static, General" and click Continue...

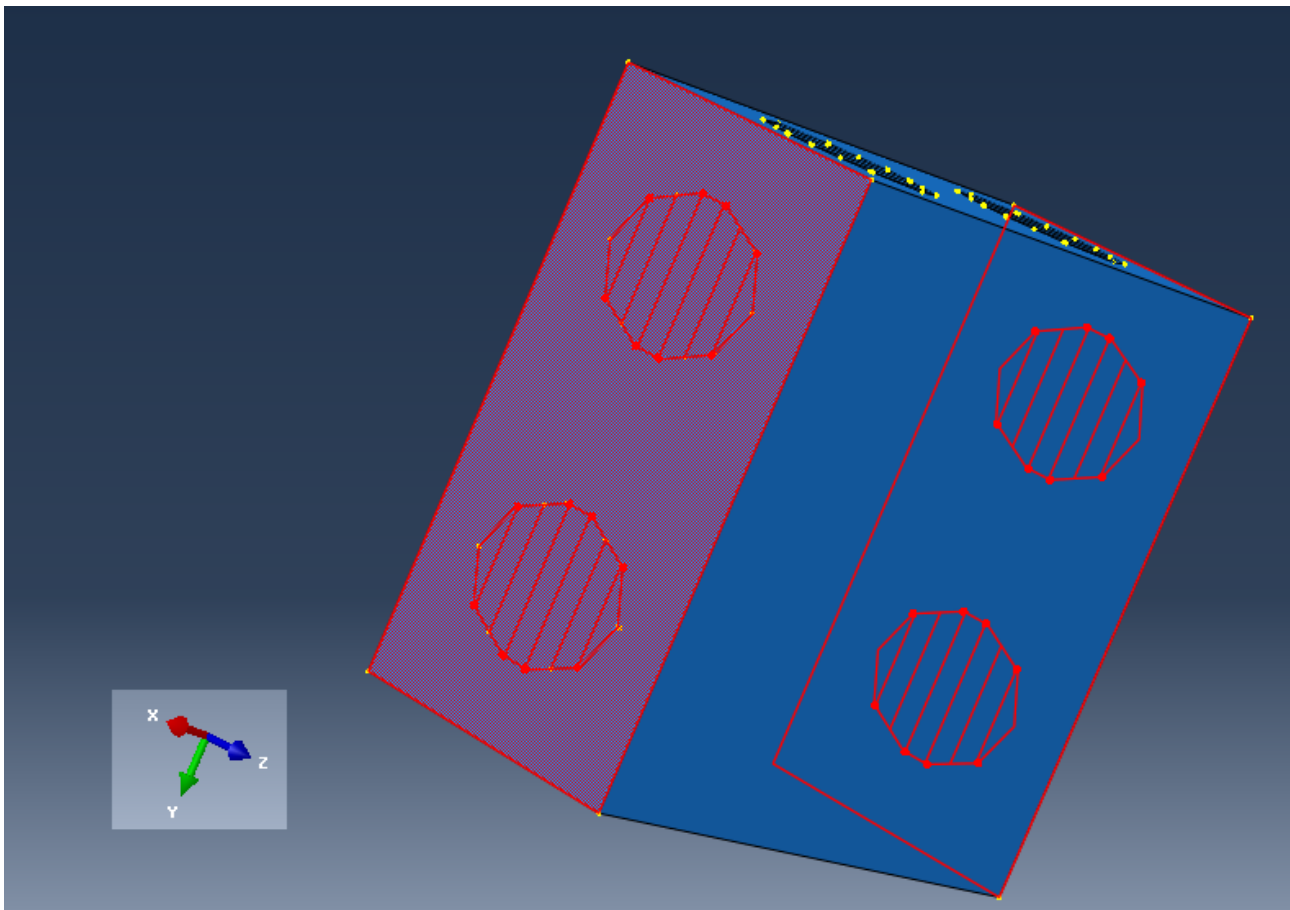
The **Edit Step** dialog box appears with the default settings for a Static, General step. Accept the default values provided for the step and click on OK.

Create Boundary Condition:

In the model tree double click on "BCs"; the **Create Boundary Condition** dialog box appears.

Name the BC "Symmetry". From the list of steps, select "Initial" as the step in which the boundary condition will be activated. In the "Category" list, accept "Mechanical" as the default category selection. In the "Types for Selected Step" list, select "Symmetry/Antisymmetry/Encastre" and click on the "Continue..." button;

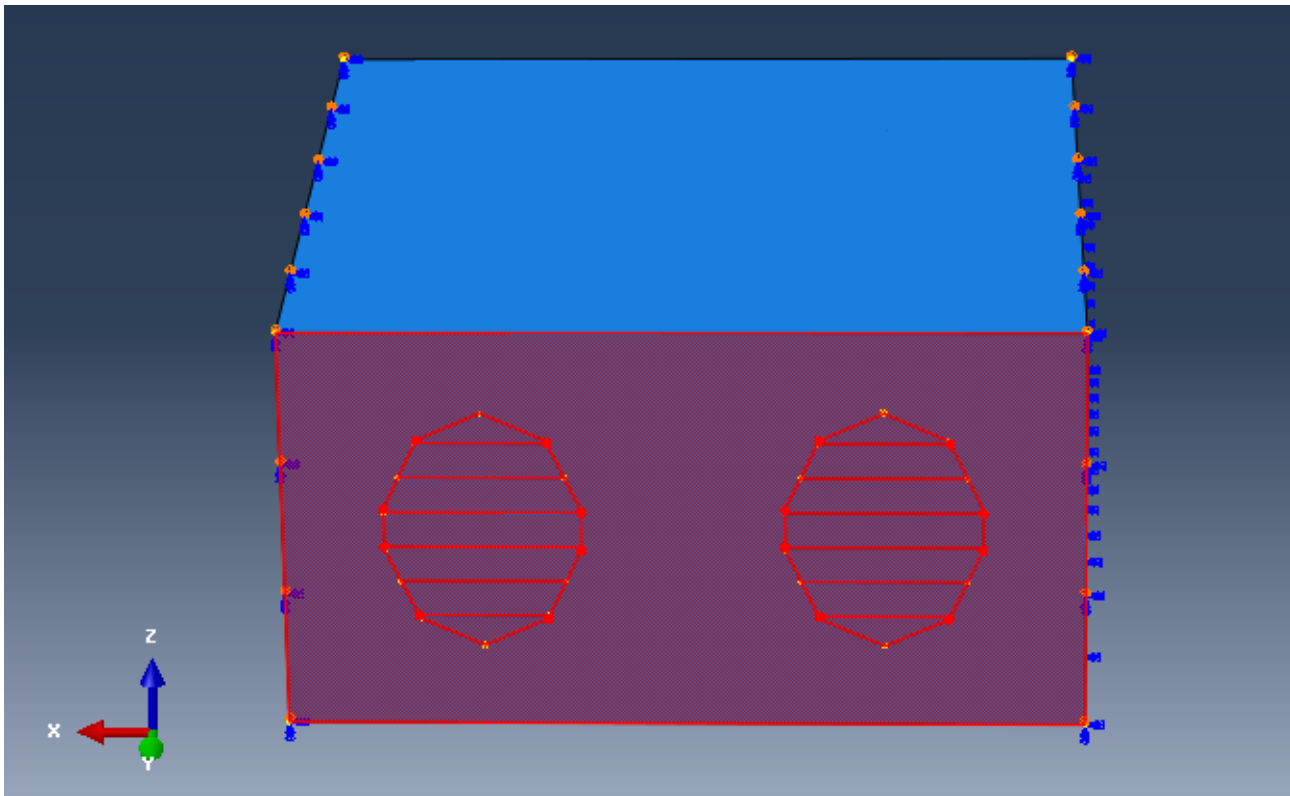
Select two of the Side-planes (opposite to each other) + the corresponding faces of the "Yarn-cut-section", click Done. In the **Edit Boundary Condition** select "YSAYMM ($U1=U3 = UR2 = 0$)" and click on OK.



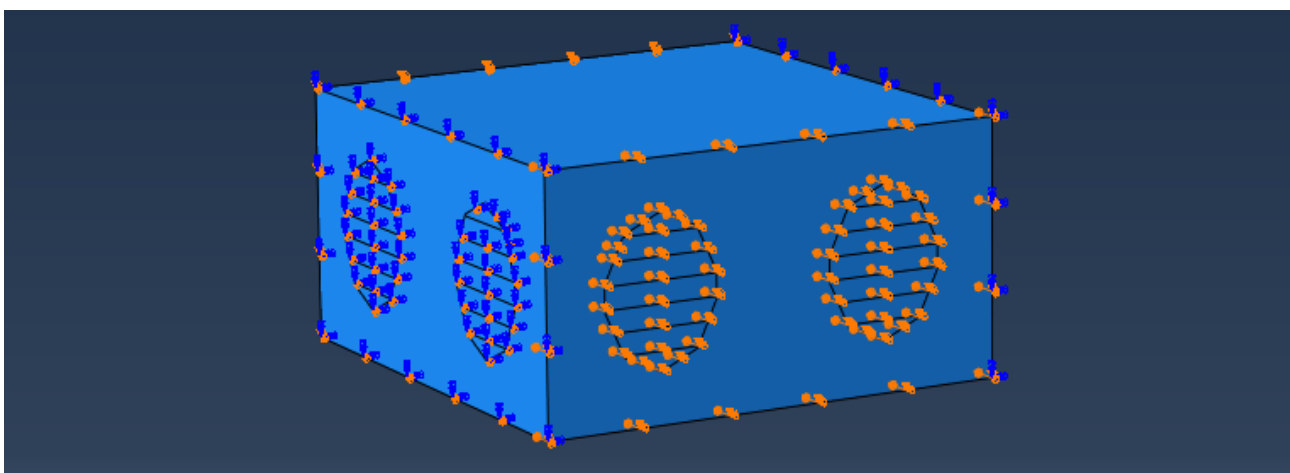
Double click on "BCs" again; the **Create Boundary Condition** dialog box appears.

Name the BC "Fixed". From the list of steps, select "Initial" as the step in which the boundary condition will be activated. In the "Category" list, accept "Mechanical" as the default category selection. In the "Types for Selected Step" list, select "Displacement/Rotation" and click on the "Continue..." button;

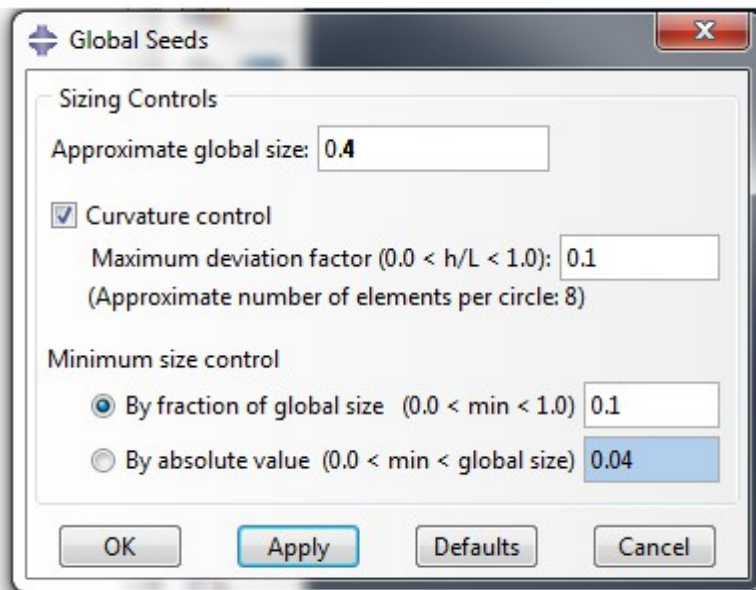
Select one of the remaining Side-planes + the corresponding faces of the "Yarn-cut-section" click Done. In the **Edit Boundary Condition** check the boxes for "U1", "U2" and "U3" and press OK.



Double click on “BCs” again; the **Create Boundary Condition** dialog box appears. Name the BC “Displacement”. From the list of steps, select “Loadstep” as the step in which the boundary condition will be activated. In the “Category” list, accept “Mechanical” as the default category selection. In the “Types for Selected Step” list, select “Displacement/Rotation” and click on the “Continue...” button;
Select the last Side-plane + the corresponding faces of the “Yarn-cut-section“. Click on Done. The **Edit Boundary Condition** dialog box appears; check the boxes “U1”, “U2” and “U3”, set U2: 0.08 and press OK. (1% of the unit cell length $8 \times 0.01 = 0.08$)

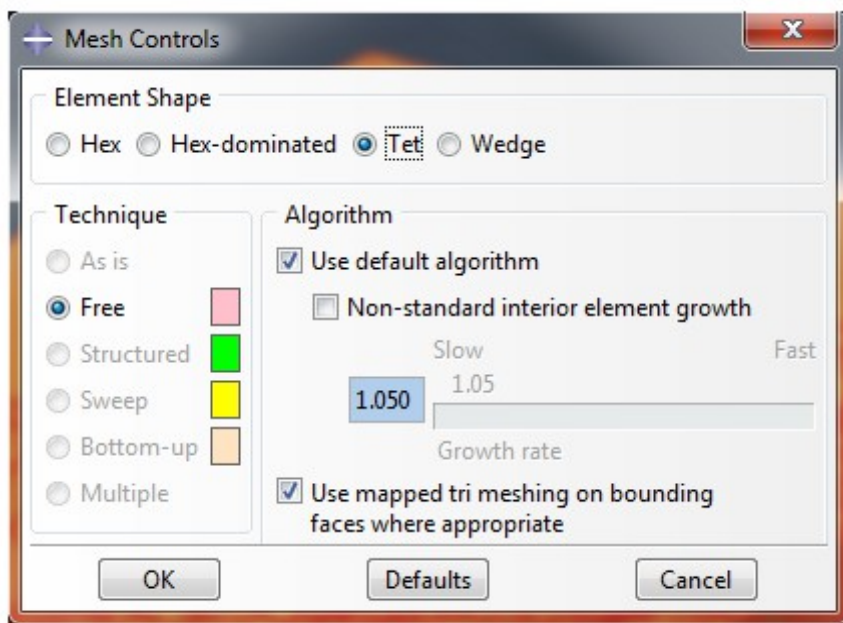


In the model tree, under Parts(11), under Plain weave, double click on Mesh (Empty). Press on Seed=>Part... and the **Global Seeds** dialog box appears. Choose:



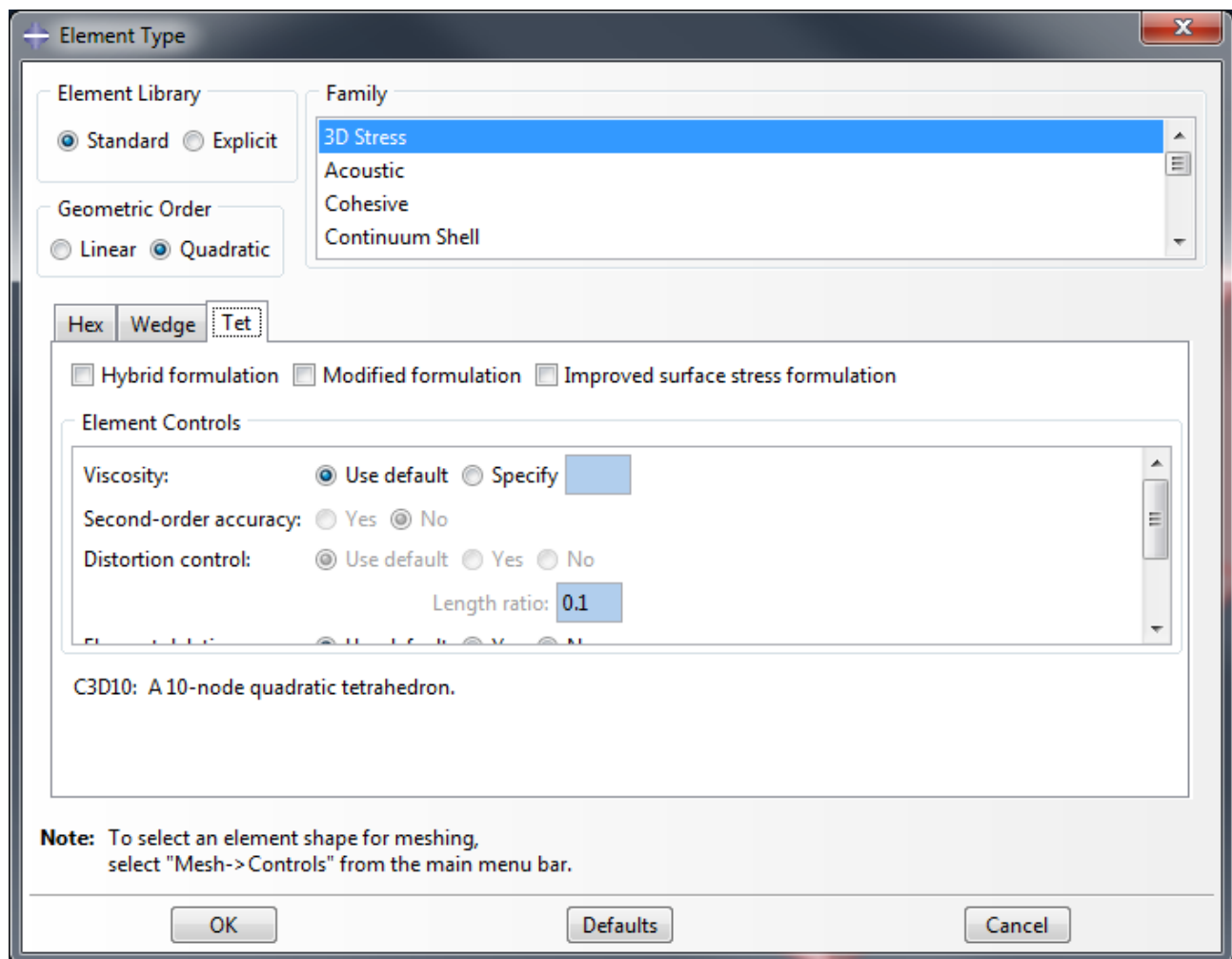
Click on OK.

Press “Assign Mesh Controls” and select the whole part, press Done. The **Mesh Controls** dialog box appears. Choose:



Click on OK.

Press on “Assign Element Type” and select the whole part, press Done. The **Element Type** dialog box appears. Choose:



Click on OK.

Press on “Mesh Part” and click on YES in the “Prompt area”

In the model tree double click on Jobs; the **Create Job** dialog box appears.

Name the job “Tensiontest” and press “Continue...”. The **Edit Job** dialog box appears, accept the default settings and press on OK.

Right click on Tensiontest under Jobs and select “Submit”