An Introduction to the Mechanics of 3D-Woven Fibre Reinforced Composites

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Abstract

The use of composite material can reduce the weight of an aircraft, but it is also associated with high manufacturing costs. The work in this thesis is a part of the EU-funded project Modular joints for composite aircraft components (MOJO). The project sets out to not only decrease the weight, but also the manufacturing cost of aircraft structures. To achieve these objectives, composite beams reinforced with 3D-woven preforms with different cross sections are proposed as joining elements.

First, the 3D-weaving process is explained, and distinguished from other weaving technologies. It is then focused on the mechanical properties of composites reinforced with 3D-woven preforms, and possible modelling strategies.

The first appended paper contains an experimental study where the in-plane and out-of-plane mechanical properties of a composite reinforced with a 3D-weave are studied. It is concluded that the out-of-plane properties are increased and the in-plane properties are decreased when compared with the corresponding properties of 2D-laminates.

In the second appended paper, the effect of three dimensional yarn undulation or crimp on the longitudinal Young’s modulus is investigated. Two analytical models and one textile mimicking model implemented in the textile analysis software WiseTex are proposed, all of which take the yarn crimp into account. The results are compared with available experimental data. The conclusion is that three dimensional crimp reduces the longitudinal stiffness non-linearly with respect to increasing yarn crimp.
Preface

The work presented in this licentiate thesis was carried out at the Department of Aeronautical and Vehicle Engineering, School of Engineering Sciences, Kungliga Tekniska högskolan (KTH). Funding is provided by the European Framework program 6, project MOJO, AST5-CT-2006-030871. The financial support is gratefully acknowledged.

I would also like to express my gratitude to my supervisor Dr. Stefan Hallström for his excellent guidance, tireless support and positive aura. The beauty of our relation is that we both learn from each other. I learn the art of science, and Stefan the art of how to hit the perfect straight backhand. I am grateful for the opportunity to work with the new and exciting 3D-woven material, and who would have thought that I could put loom builder on my resumé. Dr Nandan Khokar, the inventor of 3D-weaving, is gratefully acknowledged for introducing me to the world of weaving.

Furthermore, many thanks to my friends and colleagues at the Division of Lightweight structures for their encouragement, and lively lunch discussions. Marianne is acknowledged for proof-reading and morale-boosting. I would especially like to thank my office room mate Chris for being my partner in our ski-building project, that started as an after-hours hobby project and ended as a course in applied composites design in sports applications for the fourth year students.

Finally, I would like to thank my beloved family for your endless support and Julia, my friend inspiration and love.

Fredrik Stig

Stockholm in April 2008
As this thesis may be read outside of Sweden an explanation of the Swedish Licentiate degree may be necessary. An intermediate academic degree called Licentiate of Technology can be obtained half-way between an MSc and a PhD. While less formal than a Doctoral Dissertation, examination for the degree includes writing a thesis and a public thesis defence.
Dissertation

This licentiate thesis consists of an introduction to the area of research and the two following appended papers:

Paper A


Paper B

Fredrik Stig and Stefan Hallström, Influence of Crimp on 3D-woven Fibre Reinforced Composites, to be submitted.
Part I

Introduction
1 Background

Three dimensionally woven textiles are not only beautiful, they also have the potential to change the way aircraft and other complex structures are built.

Recently both Airbus and Boeing, the two leading aircraft manufacturers, have in their strive to reduce structural weight, dramatically increased the use of fibre reinforced composite materials in their new aircraft. The development can be exemplified by the new Boeing 787 Dreamliner which is the first commercial aircraft with both composite wings and fuselage, for which the combined weight of the composite parts account for 50% of the structural weight [1]. This trend marks a shift from using composite materials in only secondary structures (i.e. radar domes and control surfaces etc.) to also use composites in load bearing primary structures. However, the increased use of composite materials is associated with increased manufacturing costs [2].

Today the "state of the art" manufacturing method for primary aircraft structures made of carbon fibre reinforced plastics (CFRP), is pre-preg layup1. The mechanical properties of composites made from pre-pregs are characterised by high in-plane stiffness and strength and lower out-of-plane stiffness and strength. According to Naik and Ganesh [3] the majority of primary loads in aircraft structures are in-plane, and hence motivate the use of pre-preg laminates. The fuselage is one example where this is true. However, in parts such as stiffeners and stringers not all loads are in-plane, making the pre-preg laminate with its low out-of-plane lamina stiffness and strength less suitable. Composite materials with better through-thickness mechanical properties are thus desired to substitute today’s metal parts where such loads occur.

Composites reinforced with net-shaped three dimensional (3D)-fabric pre-forms have emerged as a viable option for parts like stiffeners and stringers. The 3D-fabric was developed in the 1970’s [4], and is characterised by yarns oriented not only in-plane but also in the through-thickness direction, resulting in higher through-thickness strength and stiffness. That 3D-fabric reinforcement can overcome the problems of low inter-laminar and through-thickness strength typical for traditional 2D-laminates has been known for many years, and was pointed out by Kregers and Melbardis [5] already in 1978.

The driving forces for using 3D-fabrics instead of 2D-fabrics as reinforcement in composite materials are not only their increased through-thickness properties. Other benefits include [4,6–8]:

- The option of using different types of yarns in different directions
- Flexible fibre orientation and fabric architecture

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1Pre-preg is short for pre-impregnated and indicate that the fibres are impregnated with partly hardened resin. After the pre-preg is laid up, the composite part is cured using heat and elevated pressure.
- Higher impact tolerance
- Lower manufacturing costs due to reduced labour intensity in the manufacturing processes.

The work described in this thesis is a part of the EU-funded project Modular joints for composite aircraft components (MOJO)\(^2\). The MOJO project was initiated in order to find strategies to meet future requirements of increased use of fibre reinforced composites in the primary load bearing aircraft structures. Many of the leading European aerospace companies, such as EADS Innovation Works, Premium AEROTEC, Dassault aviation, Eurocopter and Sabca, are involved together with the composite manufacturer Secar, the weaving innovation company Biteam, the research institutes DLR and CRC-ACS, VZLU and the University of Patras as well as KTH. Biteam contributes to the project with the novel 3D-weaving technology.

The objective of the MOJO project is to develop more integral composite aircraft components for a modular design using 3D textile pre-forms, which are assembled using adhesives or co-curing instead of bolts, see Fig. 1, in order to reduce cost and weight. Today, composite materials are not used to their full potential in aircraft design since the composite parts are assembled using bolts and rivets. The approach of using CFRP to replace metal using the same design is condescendingly called "black metal design". It is difficult to achieve more weight savings using such traditional joining methods since use of bolts limits the minimum plate thickness.

In the MOJO project, beams made from 3D textile pre-forms with different cross sections like (T,Π and H), are used to assemble plates in a boltless design using adhesives or co-curing. The plate thickness, and thus the weight, can then be reduced. Reduction of the number of bolts also reduces the design and assembly complexity, and hence the cost of the aircraft structure. The necessary beams available today

\(^2\)www.projectmojo.eu
are made from traditionally 2D-woven and non-woven textiles, which have to be cut, stacked and draped. There are problems associated with this methodology, the main ones being difficulty to fixate the layers to the desired shape before curing, and to achieve good enough through-thickness mechanical properties of the cured parts. To improve the through-thickness properties, various forms of stitching, braiding, bonding or z-pinning (a form a stapling with small carbon rods) have been developed, each technique having different benefits and drawbacks [10]. One of the methods proposed in the MOJO project to solve this issue is to use 3D-woven pre-forms, which have structural integrity on their own, and are easily handled before curing. Furthermore, the yarns are all interlaced in a network structure, see Chapter 3, with reinforcements in all directions, altering the failure mechanisms in a favourable way.

The target of the MOJO project is to reduce component manufacturing cost by 20-30% and reduce weight by at least 15% compared to pre-preg designs [9]. The weight reduction is achieved by the elimination of fasteners and the reduction of plate thickness previously governed by the requirements set by the use of bolts. Cost reduction is mainly achieved by the introduction of beams as joining elements which eliminate the use of bolts, and thereby reduce the cost of assembly. Boeing estimates that the number of components in a metal part can be reduced by 95% when replaced with a composite part [1]. Furthermore, the cost of manufacturing the joining elements depends on the manufacturing method. The use of dry textile pre-forms in an out-of-autoclave vacuum assisted impregnation process in an open mould is less expensive than using pre-preg in an autoclave. In addition, the weight savings achieved also decrease the in-service cost for the airline operators, when compared to current metal designs [9].

2 Objective

The main aims of the work undertaken at KTH in the MOJO project are twofold. Firstly, it involves the design and construction of a 3D-weaving loom. Secondly, the characteristics of composite materials reinforced with 3D-woven pre-forms are to be investigated, to be able to predict and tailor the mechanical properties of this novel material. The objective of this thesis is to contribute to this knowledge base. The thesis consists of two appended papers with the following objectives:

- Paper A addresses the mechanical properties of a composite material reinforced with 3D-weave by performing the following tests; tensile, compression, short-beam shear, out-of-plane and flexural test.
• Paper B describes how three dimensional crimp influences the longitudinal Young’s modulus by developing both an analytical and a textile mimicking model and examining the effects of yarn crimp.

3 Weaving

Textile manufacturing processes are broadly grouped into four types - weaving, braiding, knitting and non-wovens [11]. Each of these processes is further subdivided according to certain processing characteristics. It is possible to manufacture 3D-fabrics using all of these techniques. However, this chapter focuses on weaving, and the aim is to give a brief overview of the two fundamentally different methods of weaving processes in reference to production of woven 3D-fabrics. In the composite materials’ industry today more than one type of weave structure are labelled 3D-woven. Khokar [12–14] therefore distinguished between 2D-woven 3D-fabrics (i.e. produced by conventional 2D-weaving process), and 3D-woven 3D-fabrics (i.e. produced by 3D-weaving process) and a new class of non-woven fabrics named noobed fabrics (produced by the non-woven noobing process). These three processes and their products are categorised in Fig. 2, and further discussed in the following sections.

![Categorisation of 3D-fabrics.](image)

The fundamental operations constituting the weaving process are, in their sequential order, shedding, picking, beating up and taking up. The shedding operation displaces the warp yarns using healds\(^4\) to create a shed (a gap). The various shedding methods available have been described by Khokar [15]. The shedding operation is followed by the picking operation whereby the weft yarns are inserted in the created shed. The weft that is laid in the shed is beaten-up by the reed\(^5\) to the fabric-fell position, and thereby completing the fabric formation. To achieve continuity in the process, the produced fabric is advanced forward by the take-up

\(^4\)A heald is a flat steel strip or a wire, with one or more eyes in which warp yarns are threaded.

\(^5\)A metal comb fixed in the loom used for beating-up. The closeness of its teeth determines the fineness of a cloth.
An Introduction to the Mechanics of 3D-Woven Fibre Reinforced Composites

operation. This cycle of operations are continued repeatedly to obtain the woven fabric.

In a 2D-weaving process, two mutually perpendicular sets of yarns, the warps and the wefts, are used. The warp yarns run in the length-wise direction of the fabric, and the weft yarns in the transverse direction. This arrangement remains unchanged whether a single warp sheet is used (to produce sheet-like 2D-fabrics) or multiple warp sheets are used (to produce 3D-fabrics). This is because the weaving process continues to be identical in the production of both these fabric types.

In 3D-weaving process, one grid-like set of warp yarns and two mutually perpendicular sets of weft yarns are used. These two sets of weft yarns are thus denoted horizontal wefts and vertical wefts.

In both 2D- and 3D-weaving processes, additional non-interlacing stuffer warp yarns can be included. These stuffer warp yarns do not interlace with the wefts and hence occur linearly in the woven fabric.

A variety of basic 3D-fabric architectures are producible employing the 2D- and 3D-weaving processes, depending on how the warp is set up and how the sheds are formed. According to Whitney and Chou [16] the exact geometry of each of the basic woven architectures is influenced by several weaving parameters such as:

- Fibre or tow size
- Number of warp and weft yarns per unit width and length
- Number of warp layers interlacing with each weft yarn (weave pattern)
- Tension in the warp and weft yarns
- Tightness of the tows (resistance of deforming from its original cross-sectional shape).

3.1 2D-Weaving

Two-dimensional weaving may be utilised to produce both conventional sheet-like 2D-fabrics and some 3D-fabrics. Two-dimensional weaving is characterised by mono-directional shedding, and the interlacing of two orthogonal sets of yarns. Khokar [12] defines the 2D-weaving process as

the action of interlacing either a single- or a multiple-layer warp with a set of weft.

The manner in which the 2D-weaving process is employed for producing both 2D-fabrics and 3D-fabrics is illustrated in Fig. 3.

The two most common 2D-woven 3D-fabrics are the layer-to-layer angle interlock weave and through-the-thickness angle interlock weave (also known as 3-X weave),
The 2D-woven 3D-frabrics are usually produced as wide sheets for use in manufacturing conveyor belts, paper clothing, double cloth etc. The 2D-weaving technique also allows indirect production of a few, relatively simple, shell type profiled 3D-fabrics. Using multi-eyed healds in a conventional 2D-weaving equipment, Chiu and Cheng [17] developed a method for weaving profiled materials having double cross- (+++) and I-shaped cross-sections. Such pre-forms are woven in a flat condition and the flanges are subsequently unfolded to form a near-net-shaped pre-form.

3.2 3D-Weaving

While 2D-weaving has existed for at least five millennia, 3D-weaving is a relatively new weaving development, invented by Khokar in 1997 [13]. The 3D-weaving process is characterised by the incorporation of the dual directional shedding operation. Such a shedding system enables the warp yarns to interlace with the horizontal and the vertical sets of weft yarns. Khokar [12] defines the 3D-weaving process as

the action of interlacing a grid-like multiple-layer warp with the sets of vertical and horizontal wefts.

Accordingly, the warp yarns, the horizontal and vertical sets of weft yarns occur mutually perpendicular to each other.

The schematic of the 3D-weaving process is illustrated in Fig. 5 for a plain 3D-weave. As shown, the warp yarns are arranged and supplied in a grid-like arrangement (Fig. 5a), warps are displaced in the vertical direction to create multiple horizontal sheds (Fig. 5b), corresponding number of horizontal wefts are inserted into the created sheds (Fig. 5c), the multiple horizontal sheds are then closed (Fig. 5d), whereby the warp yarns become interlaced with the horizontal weft yarns. The
Figure 4: A Through-the-thickness angle interlock weave with stuffer yarns (blue) seen from its three principle planes and from an isometric view. Warp yarns are green and weft yarns red in the illustrations.

warps are at their level positions (Fig. 5e) in the weaving cycle. Next, the warp yarns are displaced in the horizontal direction to create multiple vertical sheds (Fig. 5f), corresponding number of vertical wefts are inserted into the created sheds (Fig. 5g), the multiple vertical sheds are then closed (Fig. 5h), whereby the warp yarns become interlaced with the vertical weft yarns. These sequences of operations are repeated once more to insert the wefts in the respective opposite directions to complete one cycle of the 3D-weaving process to obtain the woven structure in Fig. 5i.

An important feature of such a woven structure is the occurrence of pockets between any four adjacent warp yarns. These pockets can be directly filled with stuffer warp yarns (Fig. 6j) during the weaving process, although they do not interlace with the wefts. It is not necessary to fill all the pockets; select pockets can be filled with stuffer warp yarns according to needs. Furthermore, these pockets
could as well incorporate items like electrical wires, tubes, optical fibres etc.

![Diagram](image_url)

Figure 5: Illustrations of the 3D-weaving principle, seen from the warp or 1-direction.

To complement the weave illustration given in Fig. 5i, the views from the three principle planes and from an isometric view are shown in Fig. 6. If the textile architecture of such a 3D-woven 3D-fabric is compared with that of the 2D-woven 3D-fabrics illustrated in Fig. 4, a significant difference can be observed. The warp yarns in a plain 3D-weave are fully interlaced with both the horizontal- and vertical-weft yarns. In the interlock weave there is no interlacing in the 2-direction, which is a direct consequence of the fact that no horizontal shedding occurs. This is highlighted in the 1-2 plane illustrations in Figs. 4 and 6. Furthermore, the warp yarns in the 3D-woven 3D-fabric do not traverse either between ‘layers’ of the fabric or from one surface of the fabric to the opposite, but remain in their assigned planes. In the 2D-woven 3D-fabrics the warp yarns traverse between ‘layers’ of the fabric (layer-to-layer angle interlock weave) and from top and bottom surfaces, as can be observed in Fig. 4. This important difference signifies that the warp yarns in the 3D-woven 3D-fabric have a significantly lower level of crimp compared with the warp yarns of the 2D-woven 3D-fabric.

The 3D-weaving process allows direct production of woven profiled materials. Such profiled materials can be produced in solid, shell, tubular and their combination types directly. Fig. 7 exemplifies cross-sections of different profiled materials obtained directly by the 3D-weaving process. It also allows flanges with tapered
surfaces. The 3D-weaving process also offers great flexibility in creating different weave patterns, such as plain, twill and satin, in different locations of the cross-section and along the length of the profiled pre-form. Yet another possibility is the production of profiled pre-forms with bends.

3.3 Noobing

Noobing is a non-woven 3D fabric-forming process that essentially assembles three mutually perpendicular sets of yarns, and its principle fabric structure is illustrated in Fig. 8. There is no interlacing (as with weaving), interlooping (as with knitting)
Figure 7: Examples of possible cross-sections (in the 2-3 plane) of dry 3D-woven pre-forms. Courtesy of Biteam AB, Sweden, www.biteam.com.

and intertwining (as with braiding) of the involved yarns. This process was defined by Khokar [12] as

the action of producing a non-woven 3D-fabric by orientating orthogonally and binding the employed essentially three sets of yarns.

The term noobing is an acronym for Non-interlacing, Orientating Orthogonally and Binding, the main characteristics of the process and the fabric, which is called the noobed fabric. The fabric structure is also known under a variety of different other names. The most commonly used name is 3D orthogonal weave [18–22], but there are also other names for example: XYZ fabric, zero-crimp fabric, Cartesian fabric, DOS (directionally oriented structures) and polar fabric [12].

In absence of interlacing, interlooping and intertwining of the involved yarns, the constituent yarns occur linearly (without crimp) in their respective directions. As a consequence, the fabric’s structural integrity is achieved through bindings that occur on the fabric’s surfaces (excluding the end surfaces).

The noobing process is of two types: uniaxial and multiaxial. In the former process a set of grid-like arranged axial yarns are bound in the fabric-width and fabric–thickness directions. In the latter process four sets of yarns are arranged in fabric-length, fabric-width and +/- bias directions and then stitched in the fabric-thickness direction. The respective 3D-fabrics are thus denoted uniaxial noobed fabrics and multiaxial noobed fabrics.

The uniaxial noobing process has limited profiling capability – only a few solid types can be obtained (I, T, L etc. [21,23,24]). Its potential lies in engineering ready items like cylinders, cones, blocks etc. Mohamed et al. [23] state that since
there is no interlacing between the axial yarns and the binder yarns, the yarn layers are free to shear with respect to one another and also bend making the drapability good. The multiaxial noobing process has been successfully commercially employed to produce sheet-like multiaxial non-crimp fabrics.

4 Mechanical properties

The reinforcement architecture in a composite plays a paramount role for its mechanical properties [17, 25]. However, since the 3D-weaving technology is new, the appended Paper A [26] is to the authors knowledge the first article in which the mechanical properties of composite materials reinforced with 3D-weaves are addressed. The conclusions from Paper A are that the out-of-plane properties of
a composite reinforced with a 3D-weave are increased, and the in-plane properties are decreased, in comparison with corresponding properties of 2D-laminates. The short-beam-shear strength was measured higher than for the 2D-laminates. However, it was not possible to quantify to what extent since the 3D-reinforcement suppressed the desired shear failure mode in favour of crushing under the loading nose. This is in line with work by Mohamed et al. [23] who reported that a material reinforced with a noobed fabric with a fibre content in the out-of-plane direction of only a few percent tends to fail in crushing rather than in shear. Furthermore, Paper A concludes that the fibres in the through-thickness direction prohibited tensile failure in the out-of-plane tensile test, and that a new test method is needed to measure the out-of-plane strength. When compared with the 2D-laminates, the in-plane stiffness and strength are reduced due to the crimp. In Paper B, the influence of three-dimensional yarn crimp on the mechanical properties is further investigated. The conclusion from Paper B is that the longitudinal (1-direction) Young’s modulus is decreased non-linearly with increasing crimp, and models are presented which predict the influence from the crimp.

4.1 Crimp

Yarn undulation, or crimp, is one of the most important textile properties since it has a strong influence on the mechanical properties of the finished composite. There is no unified definition of crimp. Historically, crimp has had many definitions in the textile industry. Alexander et al. [27] conducted a literature study on different crimp measures and also introduced the effective crimp diameter, and the effective wave number. The textile industry currently defines crimp as

Crimp, geometrically considered, is the percentage excess of length of the yarn axis over the cloth length. It is not practicable to measure the length of the yarn axis directly and it is estimated by removing and straightening the thread under a standard tension.

here explained by Pierce [28] in one of the pioneering works from the 1930’s on textile geometry.

There is still a variety of crimp definitions within the textile composite community. The composite industry has traditionally only focused on 2D crimp, and the most common definition is the crimp ratio (CR) defined as

$$CR = \frac{\text{yarn path amplitude}}{\text{wave length}},$$  \hspace{1cm} (1)$$

and illustrated in Fig. 9. There are alternative ways to define crimp. West and Adams [29] defined the crimp angle as the largest rotation of the yarn from the horizontal plane, when analysing a tri-axial 2D braided textile composite. The crimp ratio for a twill weave is defined by Guagliano and Riva [30] as the yarn
An Introduction to the Mechanics of 3D-Woven Fibre Reinforced Composites 15

Amplitude

Wave length

Figure 9: The crimp ratio definition

thickness over cross sectional length (about half the wavelength). In this thesis Pierce’s [28] definition of three dimensional crimp is used, since it is on a more general form. One problem with using the CR for 3D crimp is that it yields two different ratios. One in the 1-2 and one in the 1-3 plane according to the direction definition in Fig. 6. The benefit of using Pierce’s crimp definition is that it results in only one crimp measure.

The stiffness of a composite is reduced with increasing crimp [31,32]. The reason is that the crimped strands want to straighten out through flexural deformation rather than carry the load entirely in tension. In this thesis a distinction is made between yarn and strand. A yarn is defined as a bundle of dry fibres, while a strand is considered as an impregnated composite yarn; hence a strand consists of both matrix and a large number of fibres. To quantify the stiffness reduction, a unidirectional (UD) composite is used as an example. Two simple models are used, both based on classical laminate theory (CLT), but with different strand path idealisations; a sine function and a zig-zag pattern (噌噌噌噌). The strand path is divided into smaller segments and the stiffness is computed for each segment. The material’s homogenised stiffness is computed using a rule of mixture approach. Two dimensional crimp is assumed and the normalised longitudinal stiffness as function of CR for the two models are seen in Fig. 10a together with results from finite element (FE) calculations by Karami and Garnich [32,33].

Crimp also affects the strength of a composite material [31,34]. Gu and Zhili [25] argue that if all strands in a fibre reinforced composite are straight, then they will react simultaneously to an external load and the full strength is achieved. However, if the strands are bent, and bent with different angles, then a portion of the strands will take up higher load and subsequently fail earlier, leading to lower material strength. Tong et. al. [34] investigated the tensile strength of a noobed composite material. In the dry noobed fabric the warp yarns press on the filler yarns (yarns in the 2-direction), which in turn become crimped. Tong et al. concluded that this crimp strongly affects both stiffness and tensile strength in the 2-direction. West and Adams [29] quantified the strength reduction of a 2D triaxially braided composite. Two different types of samples were manufactured, one where the axial yarns were allowed to crimp and one where the axial yarns were kept under tension during consolidation. Axial compression tests showed that crimp reduced the axial compression strength by 30%.

Crimp also introduces shear stresses in the matrix [32]. Bogetti et al. [31] developed a model for predicting stiffnesses and strengths in composite laminates with
The amount of crimp is dependent on weave type and various weaving parameters. The crimp also differs within a fabric depending on yarn type, i.e. warp, weft or stuffer yarn. The stuffer yarns are nominally straight, i.e. the crimp is approximately 1. Literature values of approximate warp yarn crimp for four different fabrics are presented in Tab. 1. The yarn crimp plays an important role for the mechanical properties of the composite, as discussed above. However, the fibre volume fraction of cramped warp yarns is also of importance. According to Cox et al. [18], the warp yarns in noobed, layer-to-layer and through-the-thickness angle interlock fabrics constitute only a few percent of the total fibre volume fraction. Hence, the cramped warp yarn’s influence on the in-plane mechanical properties for these fabrics is small [18].

Table 1: Typical warp crimp values for four different 3D-fabrics.

<table>
<thead>
<tr>
<th>Warp</th>
<th>Warps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer-to-layer angle interlock</td>
<td>1.2 [18]</td>
</tr>
<tr>
<td>Through-the-thickness angle interlock</td>
<td>1.3 [18]</td>
</tr>
<tr>
<td>Nobbed</td>
<td>3 - 5 [18]</td>
</tr>
<tr>
<td>3D-woven</td>
<td>1.04 (see Paper B)</td>
</tr>
</tbody>
</table>
To conclude, crimp is not favourable in a composite, since it degrades both stiffness and strength. On the other hand, it is not possible to weave without crimp, and 3D-fabrics possess many desirable properties for example excellent through thickness properties, high impact tolerance and ease of handling which may lead to cost reductions [4,6–8]. In 3D-weaves crimp is also associated with yarn interlacing which is believed to contribute with positive effects on the mechanical performance of composite materials.

4.2 Other mechanical properties

The integral structure of the 3D-weave where all warp yarns are interconnected with the neighbouring horizontal and vertical weft yarns will alter failure-modes and mechanical behaviour when compared to traditional 2D-weaves. There will also be a difference when comparing materials with different types of 3D-reinforcement, but that comparison is more speculative and better to save for future work. Instead, a more qualitative analysis is made of how the presence of through-thickness reinforcement influences mechanical properties of a material, in order to gain more insights about 3D-weave reinforced composites. For a more elaborate discussion of failure mechanisms in composites reinforced with noobed or 2D-woven 3D-fabrics, the reader is referred to [6,18,25,35].

One of the main advantages of 3D-fabric reinforcements is the increased fracture toughness. The fracture toughness is a measure of how well a material containing cracks can resist fracture. Brandt et al. [36] showed an approximate ten times increase in the force needed to generate crack propagation in a composite reinforced with a noobed fabric compared to a 2D-laminate under out-of-plane loading. Bogdanovish [20] reported an increase in crack propagation resistance of 45-50 times for a noobed fabric reinforced glassfibre/epoxy-vinyl ester composite with 2.5% fibre content in the 3-direction (see Fig. 8) over a 2D-weave counterpart. Bogdanovish also concluded that it was impossible to propagate a crack in a noobed fabric reinforced carbon fibre/epoxy composite with 8% fibre content in the 3-direction.

The increased resistance to delamination also has a positive effect on compression strength after impact (CAI). The CAI test is important for determining the damage tolerance of a composite material. The test is performed by first dropping an impactor with a certain impact energy onto the composite, and then evaluate its compressive strength using a compression test. Brandt et al. [36] showed that materials reinforced with 3D-fabrics had a lower reduction of strength after impact, and attributed it to their increased delamination resistance given by the through-thickness reinforcement.

Ding and Jin [37] examined the flexural fatigue properties for composites reinforced with a 2D-woven 3D-fabric and compared it with corresponding 2D-laminates. They concluded that while delamination is the dominant fatigue failure mechanism for 2D-laminates, the through-thickness yarn in a 2D-woven 3D-fabric prevented delamination. Furthermore, the through-thickness yarns helped to suppress the
formation of initial micro cracks and abrupt fibre failure seen in 2D-woven fabric reinforced composites. Both the 2D-laminate and the material reinforced with the 2D-woven 3D-fabric showed rapid softening in the low cycle regime. In the medium cycle regime the softening of the 2D-laminates levelled out until fibre failure, while the softening in 3D-fabric composites gradually increased during the entire test.

Grogan et al. [38] investigated the ballistic performance of armour panels with a ceramic strike face and a backing face reinforced with either a 2D-woven 2D-fabric or a noobed fabric. The results showed that the panels with noobed reinforcements had less severe delamination and fewer penetrations, which was attributed to the 3D-fibre architecture. Even though the present 3D-weaving process is not yet employed to produce plates, the 3D-fibre architecture would probably increase the resistance to ballistic impact compared to materials reinforced with 2D-weaves.

5 Modelling

A fibre reinforced composite is by nature heterogeneous on a micro scale and the mechanical properties of the material are governed by its microstructure. It is, however, impractical to also model the microstructure in structural engineering models. Instead, homogenised anisotropic material properties are used. The challenge is to determine these properties, which is usually done on a meso-scale (unit cell scale). The more complex the internal geometry is, the more difficult the task will be. For a simple cross-ply laminate CLT yields sufficiently accurate results, but as soon as woven fabrics are used, other more intricate models are needed. According to Tong et al. [4] and Lomov et al. [39] different modelling strategies may be employed.

- **Mosaic models**: Are usually used to model laminates reinforced with 2D-woven 2D-fabrics, where equivalent lamina properties are computed, as exemplified by Ishikawa and Chou [40]

- **Orienting Averaging models**: The material is divided into small sub-volumes which are treated as UD-laminas. The homogenised properties are computed by averaging the respective stiffness matrices using either an iso-stress or iso-strain assumption. For the iso-strain assumption, a prescribed homogeneous displacement boundary condition is used. This means that the strains in the building blocks are equal, assuming a perfect block interfacial bond [4]. The homogenised elastic stiffness matrix $C$ may then be computed as

$$C = \sum_i v_i C_i$$

where $v_i$ is the volume fraction and $C_i$ the stiffness matrix of block $i$. For the iso-stress assumption, the traction (applied force) is prescribed, implying constant stress in the assembled building blocks. The homogenised elastic
An Introduction to the Mechanics of 3D-Woven Fibre Reinforced Composites

stiffness matrix is subsequently computed as

\[
\frac{1}{C} = \sum_i v_i C_i.
\]

Cox et al. [41] used the orienting averaging strategy to model a composite reinforced with a 2D-woven 3D-fabric.

- **Mixed iso-strain and iso-stress models**: In a mixed iso-strain and iso-stress model, the unit cell is subdivided into sub-volumes or building blocks, in the same way as in an Orienting Averaging model. A building block contains either UD fibre reinforced composite or pure matrix. The building blocks are assembled using either an iso-strain or an iso-stress assumption. Tan et al. [42] presented three mixed iso-strain and iso-stress models for a noobed fabric reinforced material. The analytical models developed in Paper B are also of mixed iso-strain and iso-stress type.

- **Inclusion models**: The inclusion models are based on randomly dispersed inclusions in a matrix. Lomov et al. [39] point out that it is a more generalised form of an Orienting Averaging model, but without the assumption of the same internal average stress in all phases (or blocks). Mori and Tanaka [43] developed the theory on how to calculate the average stresses in each phase. Gommers et al. [44] used the Mori Tanaka theory and applied it to textile composites. One of the models in Paper B utilises an inclusion model.

- **Finite element models**: In a FE-model the material is divided into a large number of small elements, and the governing force equilibrium equations for each element are solved simultaneously using the principle of virtual work. The elements are connected through boundary conditions, and the grid containing all elements is denoted a mesh. The detailed description of the internal geometry allows for a more detailed computed stress-strain state. FE-models can be used with good accuracy and reliability for predicting the elastic homogenised stiffness properties of textile composites, as long as the correct strand path geometries are used and successfully meshed [19,39]. The main drawback with the FE-modelling technique is the need for a complex geometrical description of the fabric, leading to a complex mesh with many elements.

A detailed geometrical description of the internal geometry of a textile reinforced composite is of great importance when modelling, regardless of strategy [45]. The internal architecture, i.e. the shape of the strand paths and the strand cross-section geometries, may be obtained using different techniques. One technique is to use a composite sample and extract its strand paths using either a scanning electron microscope (SEM), an optical microscope, or a micro Computer Tomography (CT) system [46]. The first step when using an optical or scanning electron microscope is to polish the surface of the composite sample to a very fine surface finish. The next
step is to photograph the surface using one of the two microscopes. In the following steps the surface is ground away and the new surface polished and photographed, see Fig. 11. The cross-section geometry of each strand at each photographed surface is found directly from the photograph. The strand paths between each photographed surface are approximated by spline functions. With the micro CT-scan technique, a large number of two-dimensional X-ray images are taken around a single axis of rotation. The images are used to create a 3D-image of the material sample. The benefits with the CT-scan method over the microscope method is that it is non-destructive, and that it removes the time consuming sectioning and polishing. The contrast in an X-ray image is generated by the difference in density between the matrix and strands. The density difference between glass/polymer matrix is greater than for carbon/polymer matrix, and higher contrast in the images is achieved. Djukic et al. [46] succeeded to increase the contrast in images taken of carbon fibre reinforced composites by adding different types of coating to the fibres and additives to the matrix. The use of micro CT-scan to extract the textile architecture of 3D-fabric reinforced composites was validated by Desplentere et al. [47]. Another technique to obtain the internal fabric structure is to model it using analytical models, see the paragraph on WiseTex below.

When the internal fabric architecture in the composite is known, a geometrical model is built in a geometry pre-processor. The two main textile geometry pre-processors are WiseTex [39,45,48] developed at the Katholieke Universiteit Leuven, and TexGen [49] developed at University of Nottingham.

In the textile analysis software WiseTex the fabric geometry is computed using analytical models. Various fibre, yarn and fabric properties are defined in order to use the WiseTex geometry model. The main advantage is that no physical sample composite is needed, thus the predictive capabilities are increased. It is possible
to export the geometry description to different WiseTex software packages, for instance to TexComp where the elastic homogenised mechanical properties can be computed using either iso-strain, iso-stress or inclusion based models. The geometry model can also be exported as a FE-mesh with the package FETex.

In the TexGen pre-processor the strand paths are defined using designated master nodes. The strand path centreline between the master nodes are interpolated using Bezier or Cubic spline functions. The surface of a strand is defined by sweeping a two dimensional shape, for instance an ellipse, along the strand centreline. From TexGen, the geometry model may be exported as a CAD (computer-aided design) file, or directly as a FE-mesh. However, the current FE-mesh generator in TexGen is designed for composites reinforced with 2D-weaves.

In Paper B, the textile geometry of a sample composite reinforced with a 3D-woven pre-form is obtained by using the microscope method described above. The measured textile architecture is used as input for both the analytical models and the textile mimicking model. The geometrical model for the latter is constructed in TexGen, and exported to TexComp. Finally, the homogenised elastic properties are computed using both an inclusion model, and an orienting averaging model with an iso-strain assumption.

6 Contribution to the field

The concept of 3D-weaving is over 10 years old, however the use of 3D-woven pre-forms as reinforcements in composite materials is new. For the concept of composites reinforced with 3D-woven pre-forms to be accepted as an engineering material, the engineer must be able to understand the possibilities and limitations associated with the textile architecture and be able to model the material. This thesis contributes to both of these areas. In Paper A, an experimental study is performed in order to present the first assessment of the mechanical properties (both in-plane and out-of-plane) of such materials. In Paper B the influential crimp parameter is investigated and two mechanical models are proposed.

7 Future work

Since the use of 3D-woven pre-forms in textile composites is new, there are many opportunities for future work. However the main focus will be on modelling. The textile architecture of the 3D-woven fabric depends on whether the surface or the interior of a representative volume element (RVE) is considered. How this affects the mechanical properties of the finished composite is one area for future work. Other interesting topics include the balance between elastic mechanical properties ⇔ crimp ⇔ fibre volume fraction ⇔ permeability. Furthermore, one of the possible benefits of a fully interlaced yarn structure is increased fracture toughness, and out-
of-plane strength. To quantify these parameters, new models and new experimental approaches are needed.
Bibliography


Division of work between authors

Paper A

Stig performed the weaving and testing and wrote the paper. Hallström initiated and guided the work and contributed to the paper with valuable comments and revisions.

Paper B

Stig developed the analytical and TexGen models and wrote the paper. Hallström initiated and guided the work and contributed to the paper with valuable comments and revisions.
Part II

Appended papers