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Investigations of sewn preform characteristics and quality aspects for the manufacturing of fiber reinforced polymer composites

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Kaiserslautern, January 2007 Amol Ogale

To my parents

Kurzfassung

Für die Herstellung von Faser-Kunststoff-Verbunden (FKV) in kleinen und mittleren Serien sind die Harzinjektionsverfahren (LCM = Liquid Composite Molding) in Verbindung mit konturgenau hergestellten Preforms prädestiniert. Die Herstellung solcher dreidimensionaler Verstärkungsstrukturen erfolgt vor der Harzinjektion in einem eigenen Preform-Prozess. Die trockenen Fasern werden in vorgegebener Menge – orientiert am gewünschten Faseranteil des Bauteils – in die vorgegebene Orientierung gebracht und fixiert. Beim Einsatz der nähtechnischen Konfektionierung existieren Herausforderungen bezüglich einer Konsistenz in Bezug auf die Qualität der Preforms und der resultierenden Laminate sowie der erreichbaren mechanischen Eigenschaften der gefertigten Bauteile. Damit betrifft eine Vielzahl der produktionstechnischen Aspekte bei der Herstellung der Preforms die gesamte Prozesskette zur Fertigung von FKV in LCM-Verfahren.

Im experimentellen Teil der Arbeit wird der Einfluss der verschiedenen Parameter des Nähprozesses auf die Qualität der gefertigten Preforms und der Laminate und somit auf die mechanischen Eigenschaften der Bauteile untersucht und quantifiziert. Darunter fallen die Auswahl des Nähfadens, Maschinenparameter, prozesstechnische Nachteile des Nähens und Fertigungshilfsmittel, die gemäß ihrer Einflussgröße in Bezug auf den Preformprozess aber auch auf die Harzinjektion untersucht und klassifiziert werden. Zusätzlich werden die faserfreien Bereiche im Allgemeinen und die sich in Dickenrichtung ellipsenförmig ausbildenden Stichlöcher im Speziellen mikroskopisch anhand der hergestellten Laminate untersucht und ausgewertet. Es wird so eine Korrelation zwischen dem gewählten Nähfaden, den jeweiligen Nähmaschinenparametern und dem Phänomen der Ellipsenbildung nachgewiesen. Über die statistische Methode der Varianzanalyse werden aus den untersuchten Parametern die Haupteinflussfaktoren auf die Formtreue und Qualität der Preforms ermittelt.

Als ein Ergebnis der Beobachtungen innerhalb der experimentellen Studien sind die Anforderungen an den Nähfaden für das nähtechnische Preforming und das Strukturnähen dokumentiert und gemäß ihrer Bedeutung in der Verarbeitung des Verbundwerkstoffs erklärt. Es werden dadurch Selektionskriterien bezüglich des Nähfadens in Abhängigkeit von der Endanwendung geschaffen. Insbesondere werden dabei auch Untersuchungen mit Polyesternähfaden als Vertreter für den

Einsatz beim Hochgeschwindigkeits-Preforming durchgeführt. Für die Bewertung der Anwendbarkeit von Polyesternähfaden bei der nähtechnischen Konfektion von Faserhalbzeugen werden aktuelle und zukünftige Herausforderungen detailliert herausgestellt, die für einen umfassenden Einsatz bei der Herstellung von Bauteilen aus FKV überwunden werden müssen. Hierfür werden die Einflussgrößen der physischen Struktur des Nähfadens auf die Qualität und die Eigenschaften der Laminate, sowie deren Beziehung untereinander diskutiert und analysiert. Ferner werden die sich durch die Verwendung verschiedener Faserschlichten ergebenden Effekte untersucht.

Für die Bestimmung der Einflussgrößen des Nähens auf dreidimensional verstärkte Laminate werden einige auf dem Markt verfügbare Hochleistungsgarne wie Kohlenstoff-, Glas- oder Zylon-Nähfäden eingesetzt und untersucht. Nähfäden, die aus Kohlenstoff- oder Glasfasern hergestellt werden, sind sehr starr und erzeugen damit eine Reihe an Defekten. Es wurde ein darauf angepasstes und optimiertes Nähverfahren eingesetzt, um diese Laminatdefizite bei der zwei- und dreidimensionalen Konfektion zu minimieren und mechanischen Eigenschaften, sowie die Oberflächenqualität der FKV zu verbessern.

In einem weiteren Abschnitt werden der Nähprozess und die gefertigten Preforms optisch nach deren Qualität beurteilt. Dazu wurden die Nähdefekte und ihr Einfluss auf die FKV-Struktur einem Monitoring unterzogen. Die Kompaktierung der Fasern innerhalb eines vernähten und eines unvernähten Lagenaufbaus wird untersucht, sowie eine Korrelation mit den Anlagenparametern nachgewiesen. Durch diese Studie können die Zusammenhänge zwischen Nähparametern und resultierender Kompaktierung geklärt werden, wobei ebenfalls durch eine Varianzanalyse die dominierenden Einflussfaktoren herausgearbeitet werden. Abschließend wurden die Auswirkungen der Abfolge von Nähvorgängen auf die net-shape Preforms in Bezug auf den Faserverzug untersucht.

Abstract

Sewn net-shape preform based composite manufacturing technology is widely accepted in combination with liquid composite molding technologies for the manufacturing of fiber reinforced polymer composites. The development of three-dimensional dry fibrous reinforcement structures containing desired fiber orientation and volume fraction before the resin infusion is based on the predefined preforming processes. Various preform manufacturing aspects influence the overall composite manufacturing processes. Sewing technology used for the preform manufacturing has number of challenges to overcome which includes consistency in preform quality, composite quality, and composite mechanical properties.

Experimental studies are undertaken to investigate the influence of various sewing parameters on the preform manufacturing processes, preform quality, and the fiber reinforced polymer composite quality and properties. Sewing thread, sewing machine parameters, shortcomings of sewing process, and remedies are explained according to their importance during preforming and liquid composite molding. The stitches and fiber free zone in the form of ellipse that are generated in the thickness direction were investigated by evaluating the laminate micrographs. Correlation between ellipse formation phenomenon, sewing thread, and sewing machine parameters is established. A statistical tool, analysis of variance, was used to emphasize the major preform processing factors influencing the preform imperfections.

For assessing the preform quality, the observations of sewing thread requirements for preform and structural sewing were well documented during the experimental studies and explained according to their significance in the composite processing. Furthermore, selection criteria for sewing thread according to end application are discussed in detail. Investigations on polyester sewing thread as a high speed preform manufacturing element are also performed. Applicability of polyester sewing thread for the preform sewing and challenges to be overcome for its extensive utilization in the composite components are explained. Apart from this, influence of physical structure of sewing thread on the laminate quality and properties are explained and relationship between them is discussed in brief. Furthermore, challenges caused due to applied spin-finishes and sizing and remedies for the same are discussed.

Sewing threads made of high performance fibers that are available in the market, e.g., carbon, glass, and Zylon are studied for effect of thread material on through-the-thickness laminate properties. Threads made up of carbon or glass fibers are very rigid and produces number of defects, which is a major cause of concern. Optimized sewing procedure has been implemented to minimize the in-plane and through-the-thickness imperfections and to improve mechanical properties and surface characteristics of composite laminate.

Preform sewing process and final ready to impregnate preforms were analyzed for quality appearance. The sewing defects and their influence on composite structure are monitored. Preform compressibility before and after the sewing operations are intensively studied and correlation with sewing parameters is developed. Influence of sewing process parameters on the warpage and change in preform area weight are also explained in detail. Results of analytical experiments can help to improve further exploitation of sewn preforms for composite manufacturing and overall preform and laminate quality.

Abbreviations

Short form	Description
2-D	Two-dimensional
3-D	Three-dimensional
3PB	Three point bending
5H	5 harness or 5 shaft used for satin weave
AF	Aramid fiber
Altin	Altin Nähtechnik GmbH
ANOVA	Analysis of variance
ASM	NASA's advanced sewing machine
BT	Bobbin thread
CAD	Computer aided design
CF	Carbon fiber
CNC	Computer numeric control
CTC	Composite technology centre, Stade
DLR	Deutsches Zentrum für Luft- und Raumfahrt e.V.
DSC	Differential scanning calorimetry
EADS	European aeronautic, defense, and space company
FRPC	Fiber reinforced polymer composite
GF	Glass fiber
IFB	Institut für Flugzeugbau
ILSS	Inter laminar shear stress
ITA	Institut für Textiltechnik, Aachen
ITB	Institut für Textil- und Bekleidungstechnik, Dresden
IVW	Institut für Verbundwerkstoffe (GmbH)
Kevlar®	Trade name for p-aramid product from DuPont
KSL	Keilmann Sondermaschinenbau GmbH
L	Linear zone
L1	First linear zone
L2	Second linear zone
LARC	NASA Langley research centre, Virginia, USA
LCM	Liquid composite molding
LCP	Liquid crystalline polymer

LS	Lock stitch
Max.	Maximum
Min.	Minimum
MLS	Modified lock stitch
NAL	National aerospace laboratories
NASA	National aeronautics and space administration
NCF	Noncrimp fabric
NL	Nonlinear zone
NL1	First nonlinear zone
NL2	Second nonlinear zone
Nomex®	Trade name for m-aramid product from DuPont
NT	Needle thread
OSS®	One-sided stitch
PA	Polyamide
PBO	Poly(p-phenylen-2,6-benzobisoxazol)
PET	Polyester (Polyethylene terepthalate)
RFI	Resin film infusion
RTM	Resin transfer molding
RTM6	One component epoxy matrix system from Hexcel
SEM	Scanning electron microscope
SPM	Stitches per minute
T900 2-ply	Trade name for 2-ply sewing thread from Toray
Tex	Thread weight in g per 1000 m length
TFP	Tailored fiber placement
T_g	Glass transition temperature
T_m	Melting temperature
TP	Thermoplastic polymer
TTT	Through-the-thickness
UD	Uni-directional
VARI	Vacuum assisted resin infusion
VARTM	Vacuum assisted RTM
Zylon	Trade name for PBO fibers manufactured by Toyobo corporation, Japan

Symbols used

Symbol	Unit	Description
τ	[MPa]	Interlaminar shear stress
σ	[MPa]	Flexural strength of laminate
$\tau^{(u)}$	[MPa]	Interlaminar shear stress of unstitched laminate
$\sigma^{(u)}$	[MPa]	Flexural strength of unstitched laminate
$\tau^{(u)}_0$	[MPa]	Interlaminar shear stress of unstitched laminate in 0° direction
$\sigma^{(u)}_0$	[MPa]	Flexural strength of unstitched laminate in 0° direction
$\tau^{(u)}_{90}$	[MPa]	Interlaminar shear stress of unstitched laminate in 90° direction
$\sigma^{(u)}_{90}$	[MPa]	Flexural strength of unstitched laminate in 90° direction
τ_0	[MPa]	Interlaminar shear stress in 0° direction
σ_0	[MPa]	Flexural strength of laminate in 0° direction
τ_{90}	[MPa]	Interlaminar shear stress in 90° direction
σ_{90}	[MPa]	Flexural strength of laminate in 90° direction
ρ_l	[tex]	Linear density of thread
ΔT	[°C]	Change in temperature
ρ_t	[g/cm^3]	Density of thread material
$\Delta X1$	[mm]	Change in unsewn preform dimension
$\Delta X2$	[mm]	Change in sewn preform dimension
$2a$	[mm]	Major axis of ellipse
$2b$	[mm]	Minor axis of ellipse
a	[ ]	Gradient of linear regression
A_b	[mm^2]	Bonded overlap area
b	[ ]	Gradient of linear regression
F_{max}	[N]	Maximum force
L	[mm]	Support span for flexural bending test
L_o	[mm]	Overlap length
l_p	[mm]	Preform length
l_{st}	[mm]	Sewing length
M	[ ]	Slope of a curve

P	[N/mm^2]	Compaction pressure
P_f	[N]	Failure load
P_R	[N]	Rupture load
T	[°C]	Temperature
t_s	[mm]	Thickness of specimen
V_f	[%]	Final fiber volume content
V_{f0}	[%]	Original fiber volume content
V_l	[mm^3]	Laminate volume
V_m	[mm^3]	Volume of matrix material
V_t	[mm^3]	Volume of thread material
W_a	[mm]	Average sample width
w_p	[mm]	Preform width
w_s	[mm]	Width of specimen
w_{st}	[mm]	Sewing width
$\mathrm{W_t}$	[g]	Thread weight in gram
X	[mm]	Preform linear dimension (length or width)
x	[ ]	Table values for fiber volume content (regression)
y	[ ]	Table values for compaction pressure (regression)

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1 Introduction

Sewing has been used for more than twenty years to provide through-the-thickness (TTT) reinforcement in composite structures and emerged as one of the important techniques to design the textile performs. As a next step, to improve the mechanical properties, tests on the three-dimensional (3-D) reinforcement at textile fabric and prepreg were also performed [1-4]. Sewing provides a mechanical connection between the preform elements before the resin is introduced, allowing the completed preform to be handled without shifting or damage. In addition, sewing compresses the fiber preform closer to the final desired thickness. Less mechanical compression need then be applied to the preform in the tool. Nevertheless, implementation of the sewing technology for assembling the textile structures is introduced quite late [5].

Initial tests on the stitched composites were successful and turn out to be inexpensive method to improve the damage tolerance [2]. The typical laminate properties such as the damage tolerance, energy absorption behavior, especially the energy release rates, crack propagation, and crash behavior of conventional fiber composite structures can be improved by means of appropriate structural sewing [6-14].

Furthermore, the advantages of through-the-thickness sewing by means of high performance threads have been largely evaluated. For example, compression response [15], residual compression strength [16], open hole fatigue [17], interlaminar fracture [18], creep and creep rupture [19], delamination failures [20], debonding of composite joints [21] are well studied. As far as impact behavior of composite laminate is concern, apparently, the presence of stitches does not show any substantial effect on the material behavior in terms of force-displacement curve, first failure load, and indentation. However, stitched laminates exhibited about 30 % lower penetration energy than their two-dimensional (2-D) equivalent. But, the advantage of sewing in terms of impact damage resistance was evident only for high thickness composites [22].

In contrast to the large amount of work performed on evaluation of mechanical performance of stitched laminates, comparatively little research has been reported on the quality of sewing and its influence on the preform quality and laminate performance. Influence of sewing machine parameters, thread types, stitch types, etc. requires to be thoroughly evaluated.

1.1 Philosophy of sewn preforms for resin transfer molding technology

As mentioned before, sewing is a unique technique for composite materials and it can be used as mechanical and adhesive joints in composite joining [23]. Although sewing of 2-D preforms normally adds at least one extra process step, it assists much during the manufacture of laminates based on resin transfer molding (RTM) technology. From manufacturing point of view, sewing of the preforms and cutting is fully automated, consistent, and economical. Sewing as a preforming technique is versatile since the ply orientation, ply drops, and the changes in the fiber architecture can all be incorporated into the preforming process [5, 24]. Two-dimensional stitched preforms can then be assembled into the 3-D net-shape preforms. By this technique, sewn 2-D and 3-D preforms can be easily handled during the manufacture without change in the fiber distribution.

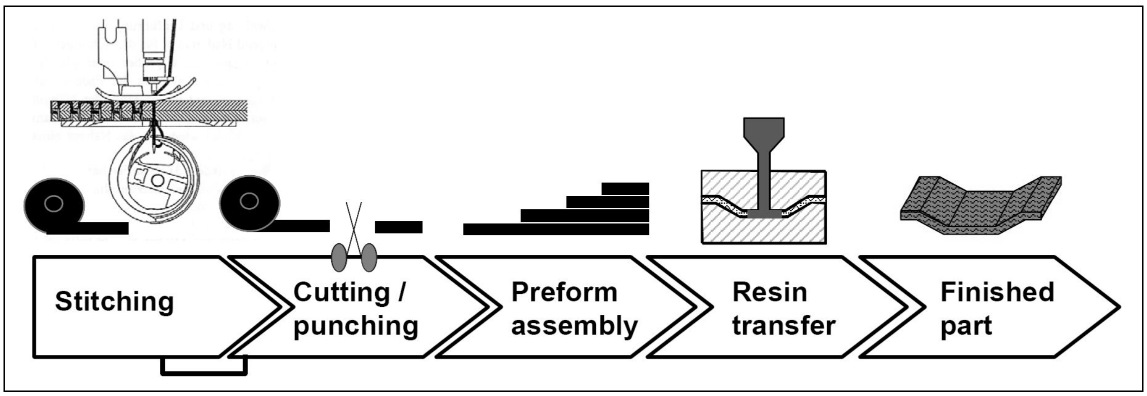


Figure 1.1: Process flow of stitched composite parts [25]

As shown in Figure 1.1, sewing of different preforms, cutting them to the required contours, and their assembly are the basic stages before the RTM processes. Net-shape preforms are essential for the efficient and fault free RTM processing [26] and sewn preform philosophy offers advantages of such a manufacturing process.

Sewing parameters such as stitch density, stitch pattern, and material properties of sewing thread can be varied to achieve the required preform geometry and characteristics. However, optimization of these sewing parameters for the enrichment of preform quality has yet to be completely designed.

Sewing process become effective as an advanced step in the process chain, immediately after the actual manufacture of the semi-finished fiber product. Nevertheless, it is generally considered damaging to the in-plane properties and deteriorating laminate quality to certain extent despite the improved out-of-plane properties. Waviness in the fiber material, as a result of the needle penetration, has a negative effect on the in-plane properties of the stitched material. For this reason, a basis must be created in which the sewing process is included as a quantifying and reproducible process of the design of an actual component [27].

Through-the-thickness sewing or structural sewing has number of advantages, nevertheless, due to the introduced seams in the Z-direction the in-plane mechanical properties, through-the-thickness laminate quality, and the surface characteristics are inferior than the unsewn fiber reinforced polymer composite (FRPC) laminates. Objectives of the present work are based on the challenges in the preform parametric issues and quality secured sewn preforms. Thorough analysis of the preform behavior and remedies for the improved quality preform have been investigated and proved.

1.2 Objectives and methodology

Analysis of various sewing aspects which are responsible for the overall preform behavior during the mold placement, matrix impregnation, and laminate behavior is vital to increase the benefits of net-shape preforming technology. Consequently, this study is focused on the examination of sewing performance at the preform and FRPC laminate stage through the following objectives.

- Sewing thread properties and parameters suitable for preform manufacturing applications and requirements for FRPC manufacturing are investigated as an initial part of this study.
- Characterization of fiber misplacement caused during the sewing operation is another cause of concern which is valid for the all kind of sewing threads. Avoiding fiber misplacement at the preform sewing stage and approaches to eliminate the amount of fiber-spread at preform stations and injection stages, thereby improve the preform and laminate quality are the next targets for this study.
- Polyester sewing threads are widely used in textile apparel manufacturing but not in high performance composites. Poor matrix impregnation, matrix-unfriendly sizing, and incorporation of foreign material in homogeneous composites are the major factors because of which composite developers are hesitant to use

polyester thread in the FRPC manufacturing. Validation of polyester sewing threads for preforming and assembly seams by assessing caused imperfections due to polyester threads and reducing its intensity by implementing suitable thread geometry and thread sizing is the immediate objective.

- During the liquid composite molding (LCM) processes, the textile preforms undergo compaction pressure. Microscopic and macroscopic examination of the preform compaction phenomenon has been implemented to analyze influence of sewing parameters on compaction behavior, effect of compaction on preform geometry, and phases of preform compaction.
- Different types of sewing threads were analyzed to investigate their influence on preforming process and role in composite mechanical properties. Though the polyester threads are only used for preform joining and not for laminate toughening, change in mechanical properties were considered for the intensity of thread-matrix bonding.
- Preform manufacturing parameters influencing the preform quality, e.g., sewing sequence, warpage, area weight, etc. have also been studied. This study helps to optimize sewing sequence for particular preforming applications including achieving net-shape preforms of required quality.

2 Three-dimensional preforms used in composite manufacturing

The application of 2-D laminates in some critical structures in aircraft and automobiles has also been restricted by their inferior impact damage resistance and lower TTT mechanical properties when compared against traditional metallic components. The low through-thickness properties, such as stiffness, fatigue resistance, and strength have impeded the use of 2-D laminates in thick structures subjected to high through-thickness and interlaminar shear stresses. Properties of 2-D laminates can be improved to a certain extent by the use of toughened resins or fiber interleaves. This solution can not overcome all the challenges associated with the laminate manufacturing [28].

To prevail over majority of challenges related to manufacturing and mechanical properties of laminates, considerable efforts has been taken over past 35 years to the development of advanced polymer composites reinforced with 3-D fiber architectures. Apart from embroidery and Z-rod insertion, most attention has been given to the 3-D composites manufactured by the textile techniques of weaving, braiding, sewing, and knitting [29]. Composite structures made with 3-D textile fabrics are potentially less expensive to manufacture and provide better TTT mechanical properties than the composites made with the traditional 2-D fabrics. In this chapter, popular 3-D preform manufacturing techniques and need for sewn preforms are discussed in brief. Furthermore, the state-of-the-art of the sewn preforms and internationally available sewing based preforming facilities are described.

2.1 Direct preforms

3-D woven fabrics

A 3-D weave contains multiple planes of nominally straight warp and weft yarns that are connected together by Z-fibers to form an integral structure (Figure 2.1). Warp and weft rovings are aligned in 0° and 90° direction respectively. The Z-fibers can be aligned in the warp direction or inserted in the weft direction and their path through-the-thickness of the preform is controlled by the lifting sequence. Typically a computer controlled jacquard loom is capable of weaving 3-D preforms. However, less complicated weaving machines, like handloom, can also be used for manufacturing the 3-D woven preforms. Most common classes of 3-D weaves are shown in Figure 2.2. Within each class, there are several parameters that can be varied. Interlock weaves can be categorized by the number of layers that the Z-fiber penetrates.

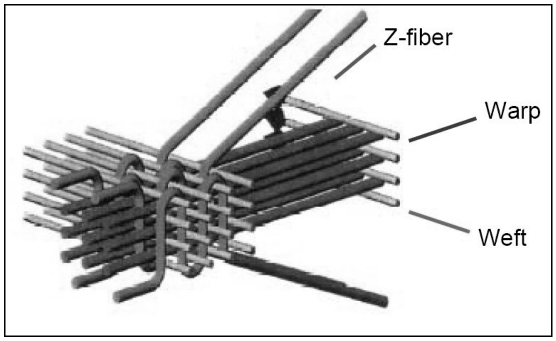


Figure 2.1: Schematics of 3-D weave (Source: 3tex) [30]

In orthogonal weaves, the warp rovings passes through-the-thickness orthogonal to both in-plane directions. Interlock weaves are sometimes manufactured without straight warp yarns (stuffers) to produce a composite which is reinforced predominantly in one direction. It may also be fabricated with weft rather than warp yarns used for interlock.

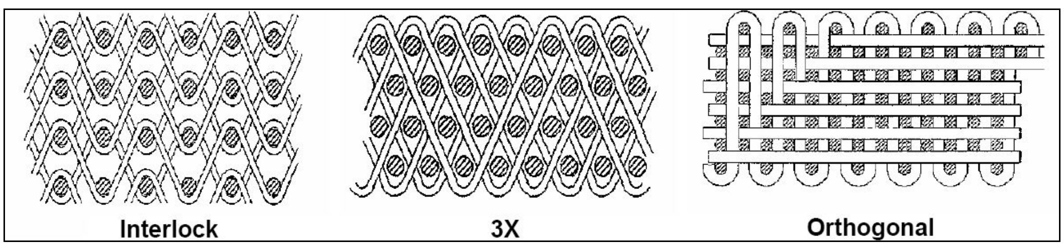


Figure 2.2: Types of 3-D woven structures

Another solution to manufacture 3-D preform is to stitch the additional 2-D fabric plies oriented at ±45° onto the woven preform (Figure 2.3).

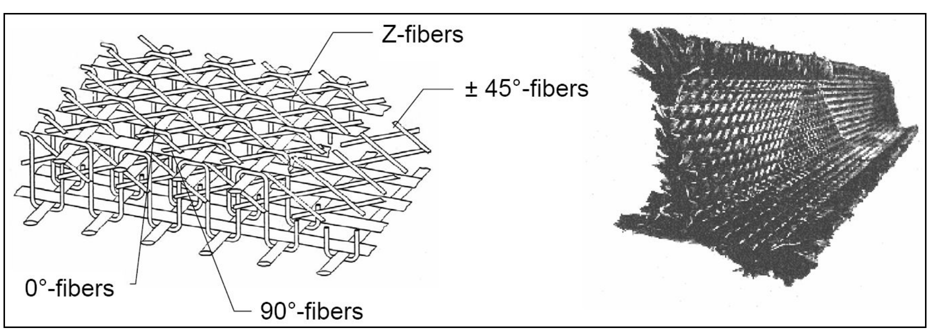


Figure 2.3: Schematic of woven fabric and 3-D woven T-section [31]

Using the multi-warp weaving method, various fiber architectures can be developed including solid orthogonal panel, variable thickness solid panels, core structures or truss like structures. Orthogonal cross-lapped fabrics can be formed by placement of yarns at right angle to each other, typically in either rectangular or cylindrical space. There is no interlacing or other form of entanglement to hold the structure. Yarn is alternately laid between the edges in alternating orthogonal direction to create thick structure. Table 2.1 shows comparison between some multi-axial weaving techniques.

Table 2.1: Comparisons between different multi-axial weaving techniques [32]

Bias fiber placement	Uniformity of bias fiber layers	Through-the-thickness reinforcement	Multiple layers
Rapier	No	Yes	Yes
Lappet	Yes	No	No
Screw shaft	No	Yes	Yes
Split reed	Yes	Yes	Yes
Guide block	Yes	Yes	Yes
Bobbin (polar)	Yes	Yes	Yes

Research into the 3-D weaving process and the properties of 3-D woven composites over the past 20 years has revealed a number of advantages over traditional laminates. One important advantage of 3-D weaving is that preforms for a composite component with a complicated geometry can be made to the near-net-shape. This feature can greatly reduce the cost of a component by reducing material wastage, the need for machining and joining, and the amount of material handled during lay-up. Another benefit of the 3-D weaving is that fabrics with a wide variety of fiber architectures can be produced with controlled amount of Z-fibers for the TTT reinforcement. Property wise important advantage of 3-D woven composites is high ballistic impact damage resistance and low-velocity impact damage tolerance [28], which have been a major challenge with the use of 2-D laminates in military aircraft structures. Furthermore, the superior damage tolerance of 3-D composites occurs because the through-thickness Z-fibers are able to arrest or slow the growth of delamination crack formed under an impact loading. Z-fibers are also responsible for the increase in tensile-strain-to-failure values and mode-I interlaminar fracture values than the UD carbon-epoxy laminates [33].

Despite the advantages and potential benefits of 3-D woven composites, these materials have failed to find many commercial applications. The reasons behind this are: difficult and expensive to manufacture quasi isotropic fabrics, 3-D composites have lower tension, compression, and torsion properties. In-plane mechanical properties and failure mechanisms are not very well characterized and, poor understanding of the influence of weaving parameters on the preform architecture and composite properties. Use of 3-D fabrics in current form in the aerospace industry is quite challenging.

Spiral / polar fabric

The fabric is composed of interlaced warp and weft elements in such a way that warp rovings are arranged in spiral direction and weft rovings are positioned more in the radial direction. Warp rovings are laid according to the required fabric width and it also depends on the outer and inner diameter of the spiral fabric to be woven. A special kind of weaving mechanism (weft beat-up) enables to lay a weft thread in curved direction, thus curved fabric geometry can be formed. The amount of weft thread per unit area depends on the position of the geometry whereas the amount of warp is always constant throughout the fabric (Figure 2.4) [31].

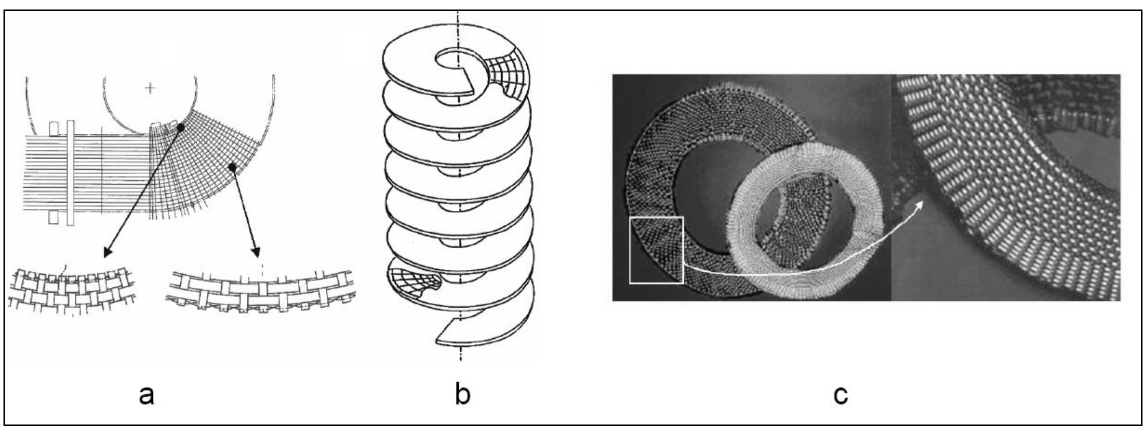


Figure 2.4: Spiral fabric or polar woven fabric: a) and b) schematic diagram of weaving technique and fabric, c) CF woven fabric

The spiral fabrics have a higher specific elastic modulus in the warp direction than those positioned in the radial direction. This construction helps to manufacture round shaped FRPC laminates. Though this type of fabric geometry has number of advantages in net-shape preforming, there are very limited studies carried out on laminate performance and its industrialization. Furthermore, classical woven fabric defects are still there and this type of fabrics are only suitable for circular or semicircular parts with specific inner and outer diameter.

Noncrimp fabric

Noncrimp fabric (NCF) materials provide an adequate response to the demand for an improvement against damage tolerance in general [7], particularly delamination [34], as well as substantial cost reductions. These composites are obtained by stacking blankets which are typically made up from 2 to 4 layers of roving stitched together through their thickness. Each layer which can be oriented in several directions is made up of tows of fibers placed side by side. In terms of cost reduction, the improvement comes both from the easier handling/lay-up process and from the use of economical tows containing up to 400 k filaments.

The multi-axial warp knit process ties yarns of primary fibers in layers with 0°, ±45°, and 90° orientations together. The knitting is done with fine polyester threads, which amounts to a small percentage of the total weight. During knitting, the polyester threads are passed around the primary yarns and one another in interpenetrating loops (Figure 2.5). The mechanical properties of the stack of layers can be controlled by selecting the roving weight in each of the four orientations. The knitted stacks form building blocks which can be laminated to form the structures with desired thickness. The knitted stacks can also be stitched together in a second step.

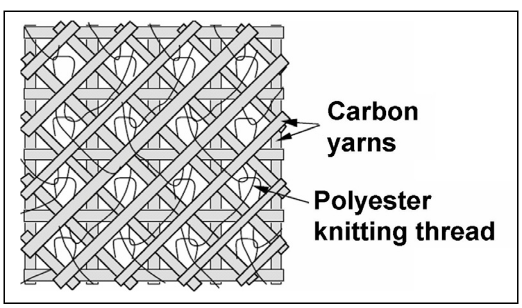


Figure 2.5: Multi-axial warp knitted fabric

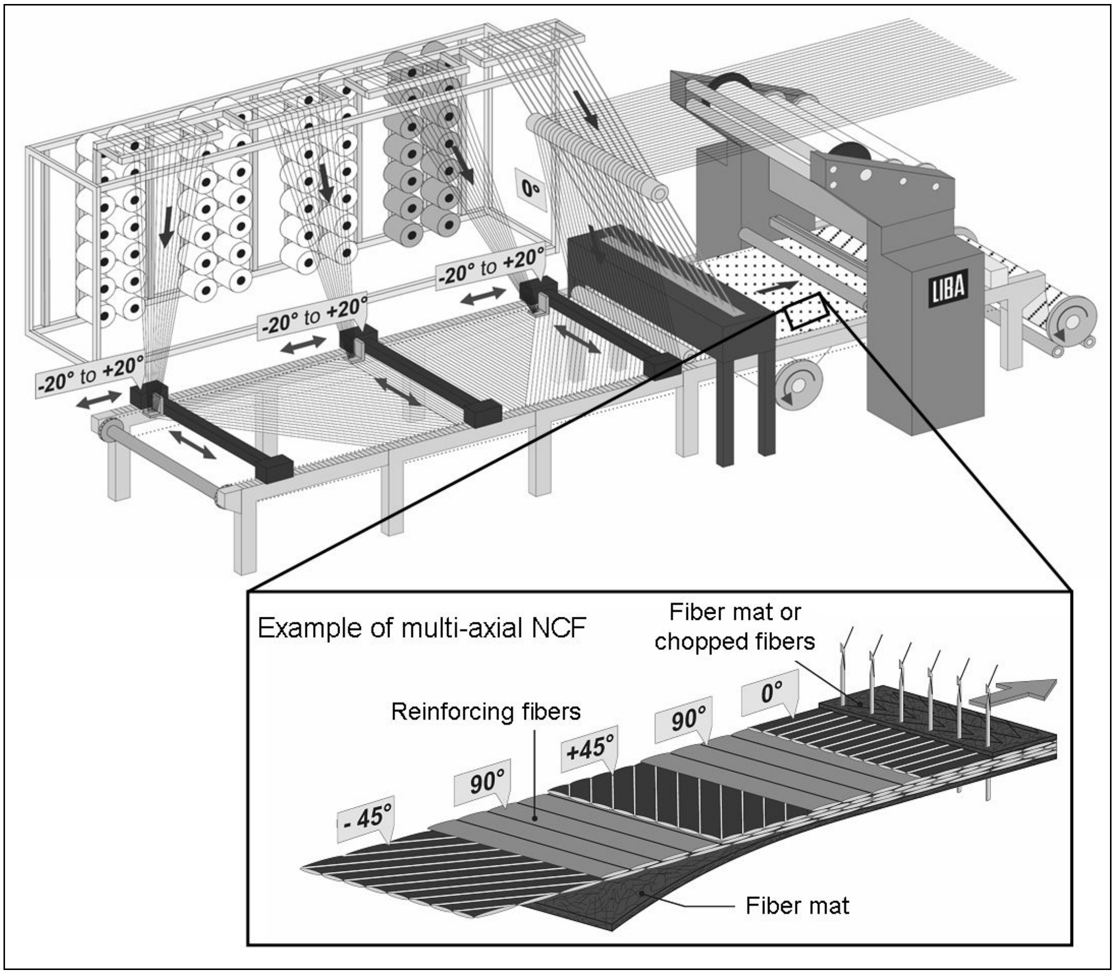


Figure 2.6: Schematic representation of a NCF MAX3 concept [35]

NCF allows manufacturing reinforcements with different fiber orientation without waviness in the structure. The fiber orientation angle can be set from +20° to -20° to the production direction. The modern NCF machines (Max 5, Liba Maschinenfabrik GmbH) can provide advantages of reduced waste of weft ends and economical production of lightweight and heavyweight carbon fiber weft layers (80 g/m^2 - 300 g/m^2 per layer) [35]. Figure 2.6 shows a schematic diagram of a NCF manufacturing machine with 0/90/±45° oriented fabric sample.

Bi-axial reinforced knitted fabrics are composed of weft and warp yarn layers which are held together by a sewing yarn system. The simplest structure of a bi-axial reinforced knitted fabric is shown in Figure 2.7 (manufactured by Institut für Textil- und Bekleidungstechnik, ITB, Dresden). Reinforcing yarns, e.g., glass fibers, carbon fibers, or aramid fibers (AF) for instance, Kevlar® can be used within all yarn systems (warp and weft). The reinforcing yarn systems provide the necessary composite strength and stiffness and the knitting structures provides the high drapability of the preform as well as the good impact behavior of the composite material [36].

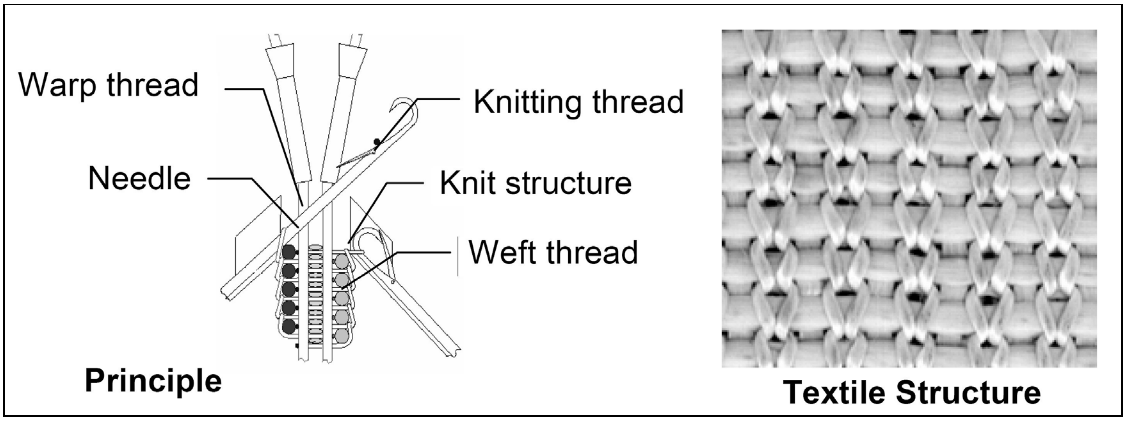


Figure 2.7: Bi-axial sewing/knitting (Source: ITB, Dresden) [37]

In case of bi-axially knitted NCF, introduction of sewing definitely brings an improvement against delamination [34]. However, the introduction of sewing has strong drawbacks as it induces heterogeneity at the scale of the tows, e.g., resin pockets forming between tows, unknitted roving loops, and filament breakages can be induced during the needle penetration. Apart from this, industrial manufacturing of net-shape preforms is not yet well established and limited information is available on the basic laminate characteristics.

Braided structures

Braiding was the first textile process used to manufacture a 3-D fiber preform for a composite. There are various braiding technologies available for composite manufacturing [38]. This process was developed in late 1960s to produce 3-D carbon-carbon composites to replace high temperature metal alloys in rocket motor components in order to achieve weight savings up to 50 % [28, 39]. Braids are formed by interlacing three or more yarns so that each yarn passes over and under one or more number of rovings. Braids are divided into two types: (1) flat braids, in the form of narrow flat tapes and (2) tubular braids, which may be hollow or have a center core. Traditional 2-D braiding involves a series of yarn carriers that follow intersecting circular paths so that the yarns interlace to form a tubular fabric. 3-D braiding can produce thick and net section preforms, in which the tows are so intertwined that there may be no distinct layers.

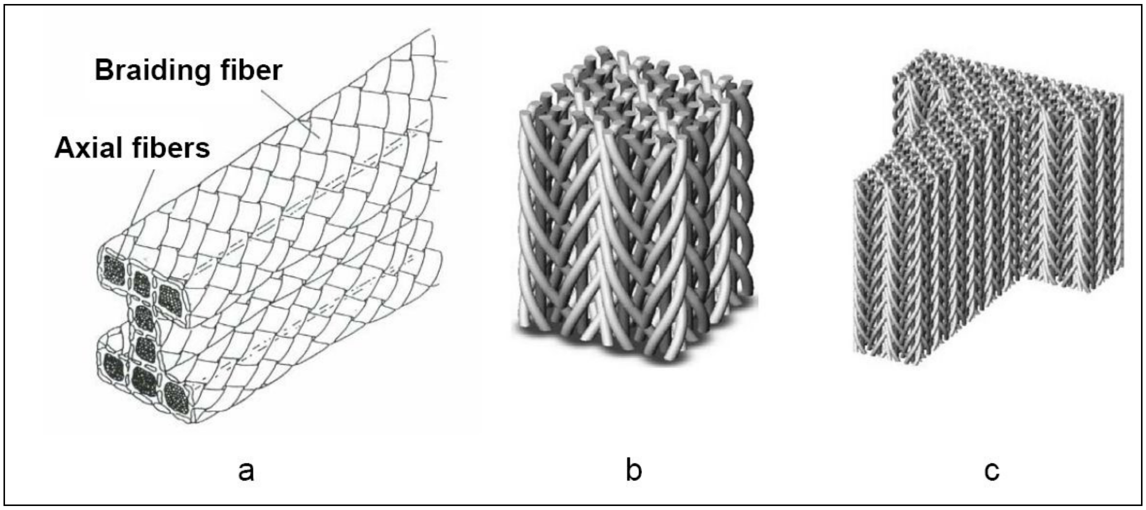


Figure 2.8: Braided stricture a) schematics of I-section, b) braided fiber orientation, c) T-sections

As far as 3-D breading is concern, there are number of advantages. Braiding has ability to produce complex near-net-shape preforms. Braiding process can be automatically controlled, which increases production and preform quality including reproducibility. The composite manufactured from braids are less expensive and simple to manufacture. From the mechanical properties point of view, braided composites have higher delamination resistance and impact damage tolerance, superior crashworthiness properties [29], and less sensitive to notches [28].

Recently, Mercedes Benz has used braiding technology for manufacturing SLR's longitudinal members. Mercedes-Benz requires a cycle time of just 12 minutes to manufacture the complex fiber structure of the longitudinal members using a braiding machine. This example illustrates the potential production capacity that this innovative manufacturing technology offers for the future [40].

Despite of these advantages, the applications for 3-D braided composites have been limited. Almost all 3-D braiding machines are still under development. Most of the available machines are only capable of the narrow preforms. The spools in 3-D braiding machines are small because they are continuously moving in the production of the preform. The mechanical performance of large 3-D braided structures has not been extensively studied. However, stiffness and strength of composites are greatly lower than 2-D laminates. The strength and fatigue performance models have not been developed. Furthermore, the mechanical properties are strongly influenced by the edge condition of the braid. The use of braided composite in the composite industry is depends on the process cycle time and costs involved in the complete production [28].

2.2 Special preforms

Bindered preforms

A key step in direct processing is the manufacture of the preform itself. Pre-draped and contour-arrested textile geometries are considered as a net-shape preform for the RTM processing. Manufacturing of such preforms can be possible by using binder technology and contour setting by applying heat and pressure. It is essential to control the fiber orientation throughout the process from the lay-up of the different plies to the closing of the tool. To achieve such control, some of the manufacturers began developing binders in dry powder form, over 15 years ago. These products are applied to one or both sides of the reinforcement and require heat to consolidate the preform.

The example shown in Figure 2.9 is an aircraft engine fan blade containment using aramid reinforcement and Figure 2.10 shows qualified carbon fiber contour woven preform in process for a commercial aircraft application. Generally for this application, a thermoplastic binder material is used which facilitates reheating for correcting the preform shapes for final contour.

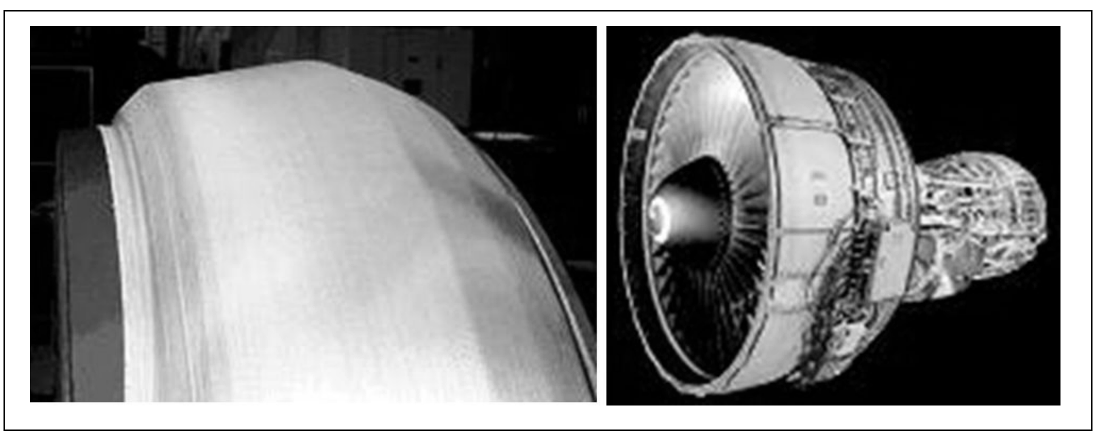


Figure 2.9: Contour fabric: (l) 3-D preform, (r): product with 3-D preform [41]

Apart from the thermoplastic binders, now a day, thermoset binders based on multifunctional matrices (e.g., toughened matrix) can be used. The bindered fabric can be shaped to the required contour and then by application of heat and pressure the thermoset binder sets the fabric geometry to the final shape. Typically, 1-5 % of binder can be applied on the basic textile material. As far as the preform quality is concerned, there are no TTT reinforcing fibers introduced, therefore, the separation of reinforcing material has been avoided. The overall quality of bindered preform is much better but it is relatively expensive, there is no through-the-thickness reinforcement possibility, and binder qualification for various applications is a must.

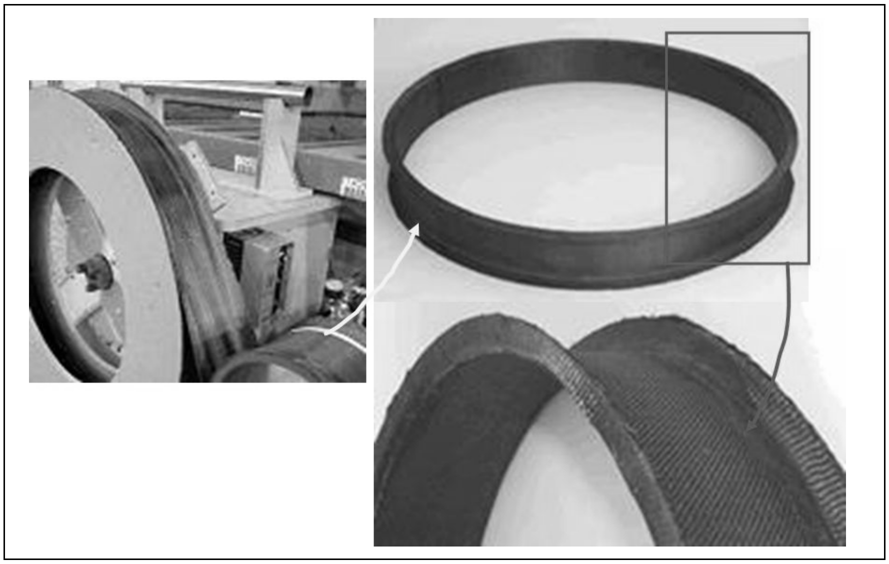


Figure 2.10: 3-D preforming C-section [41]

Laminate peel strength and toughness can be increased by the use of modified binder systems. But the presence of about 2.6 wt % of the polyester binder reduces the Mode I interlaminar fracture toughness and apparent interlaminar shear strength of the glass epoxy-amine system by about 60 % and 25 %, respectively. Moreover, the glass transition (T_g) of the matrix polymer within the interlaminar region decreases about 6 °C due to the presence of the binder [42]. Both the compressive strength and modulus values increase up to 3 wt % of the binder, but these values decrease with further addition of the binder. Furthermore, the binder amount has some considerable effect on the damage extension of the impacted composites [43]. As far as bindered preform manufacturing in concern, for each preform geometry separate mold is needed. Apart from this, tooling and temperature cycles which increases the manufacturing time has to be considered.

Z-pinning technology

Through-the-thickness pins, known as 'Z-pins', have been anticipated to increase delamination strength and toughness [44, 45]. These pins are made from structural materials such as pultruded carbon fiber-epoxy composite, glass fiber composite, or titanium alloy. The Z-pins comprise rods inserted in the through-thickness direction (the Z-direction) of a laminated composite, and they serve to stitch the material together by a combination of friction and adhesion. The insertion process is as follows. Rods of diameter 0.1 to 1 mm are cut to a length of approximately 4 mm, with chamfered ends to improve the ease of insertion. They are inserted into a polymer foam carrier and arranged in a square pattern. The foam carrier is then placed on one face of an uncured composite laminate and an ultrasonic horn is used to drive the pins into the composite laminate. The laminate is air cooled in a freezer, allowing the excess pin material to be sheared off with a razor blade. Finally, the plate is autoclaved using the standard cure cycle for the composite laminate. This approach to through-thickness reinforcement offers an alternative to sewing, and can provide much higher area densities of reinforcement [46]. Figure 2.11 shows a cross-section of laminate containing Z-pins or Z-fibers.

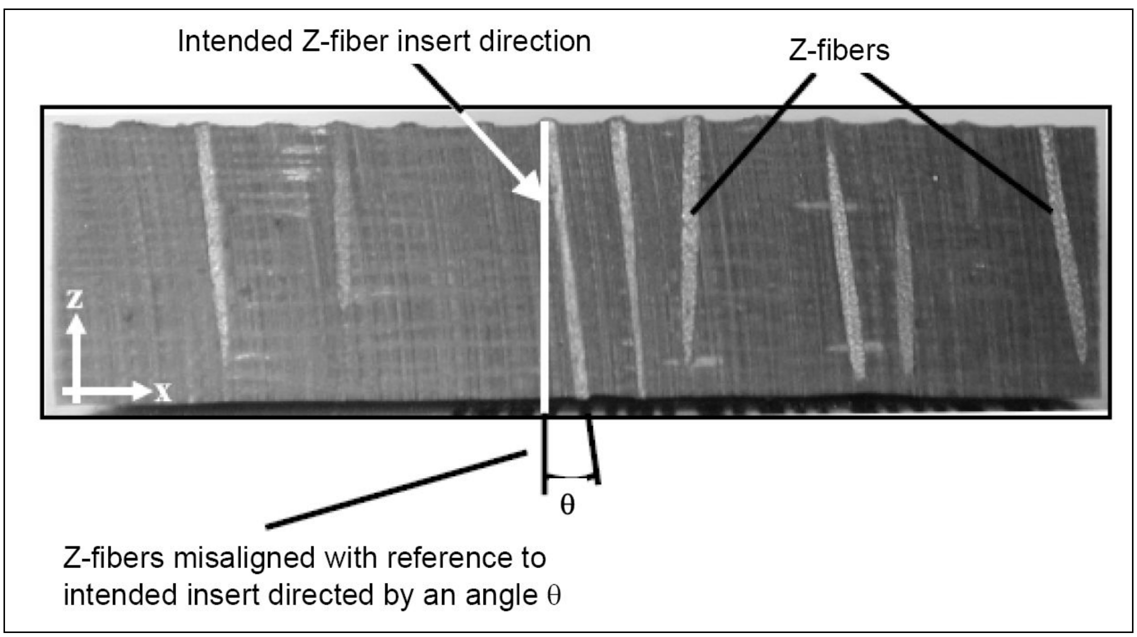


Figure 2.11: Laminate containing Z-pins [48]

The preform and laminate quality is dependent on diameter of Z-pins and angle of insertion. Figure 2.11 also shows misaligned pins inside the laminate structure.

During delamination growth, a reinforcing z-pin provides a closure force against the opening crack. With the same area density, small pins provide more efficient reinforcement than big pins [47, 48]. In literature, it states that z-pins reduce the in-plane strength of composite laminates [49]. The observed tensile strength of the uni-directional (UD) composites is reduced by approximately 27 % while the compressive strength is reduced by at least 30 % due to the presence of the Z-pins. The compression tests on the Z-pinned specimens show a clear correlation between the knock-down of compressive strength and the degree of fiber misalignment [46].

In variety of composite applications, advantages of above mentioned preforming techniques are considered and some modifications in the processes are also made. Nevertheless, the limitations of various 3-D preforms are still present which can not be neglected. A technology of sewn preform has been brought into the composite manufacturing field years ago, which has potentials to overcome the disadvantages of available 2-D and 3-D structures by combining their advantageous factors together.

Sewn preforms

The major manufacturing advance in recent years has been the introduction of resin transfer processes which allows sewing of dry preforms, rather than prepreg material. Sewing process basically involves high tensile strength sewing threads (e.g., glass, carbon, or aramid) through an uncured prepreg laminate or dry fabric piles using an industrial sewing machine. Sewing has also been carried out using polyester thread, although Kevlar® and glass are the most popular high performance thread materials, due to their advantages in strength and flexibility. Nowadays, variety of carbon threads are available for sewing but the basic challenges of abrasion and loop strength makes it unsuitable for the high speed machines.

Through-the-thickness threads have been stitched into composites to densities ranging from 0.4 up to 25 stitches/cm^2, however, most of the sewing operation is performed between 3 and 10 stitches/cm^2. A variety of sewing machines can be used to stitch composites. Sewing is occasionally used to reinforce prepreg laminates, however, tackiness of the uncured resin makes sewing difficult with some of the in-plane fibers being broken and distorted. This damage can adversely affect on the mechanical properties. Because of this shortcoming, sewing process is used mostly to sew the dry fabric preforms before they are consolidated with a resin into a composite. Here, it allows sewing through a thicker material which greatly reduces damage to the in-plane fibers.

In addition to enhancing the damage tolerance, sewing also aids fabrication. Many textile processes generate preforms that cannot serve as the complete structure. For example, bias plies usually must be attached to 0°/90° weaves or stiffeners to a skin. Sewing provides a mechanical connection between the preform elements before the resin is introduced, allowing the completed preform to be handled without shifting or damage. In addition, sewing compresses the fiber preform closer to the final desired thickness. Less mechanical compression need then be applied to the preform in the tool.

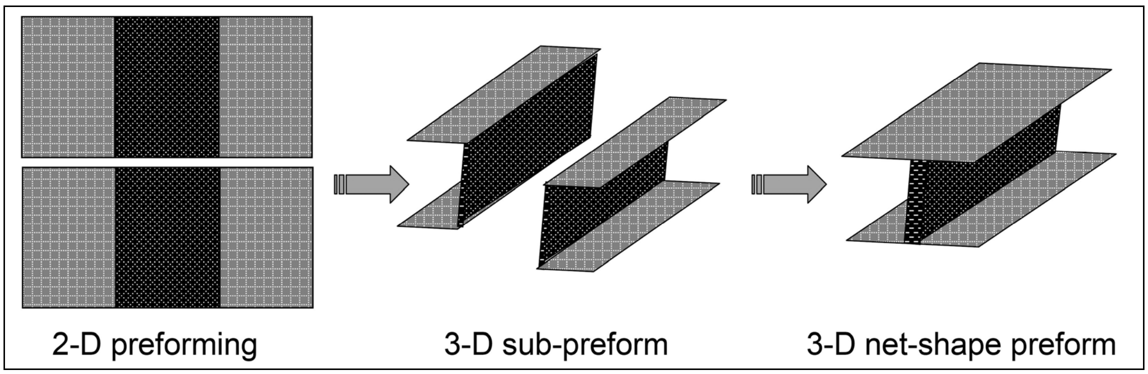


Figure 2.12: schematics of sewn preforms process flow

In many applications, strength and damage tolerance requirements would be fulfilled by less than one volume percent of sewing fibers (1 % of component volume). However, the minimum volume of sewing is set by the fabrication process. While there is considerable latitude in stitch density, the lower bound in current technology sometimes exceeds the amount needed, thus, unnecessarily sacrificing in-plane properties [50]. An optimized solution between required stitch density for enhancing 3-D properties, end-geometry compaction, and minimum deterioration of in-plane properties need to be found according to the end-use.

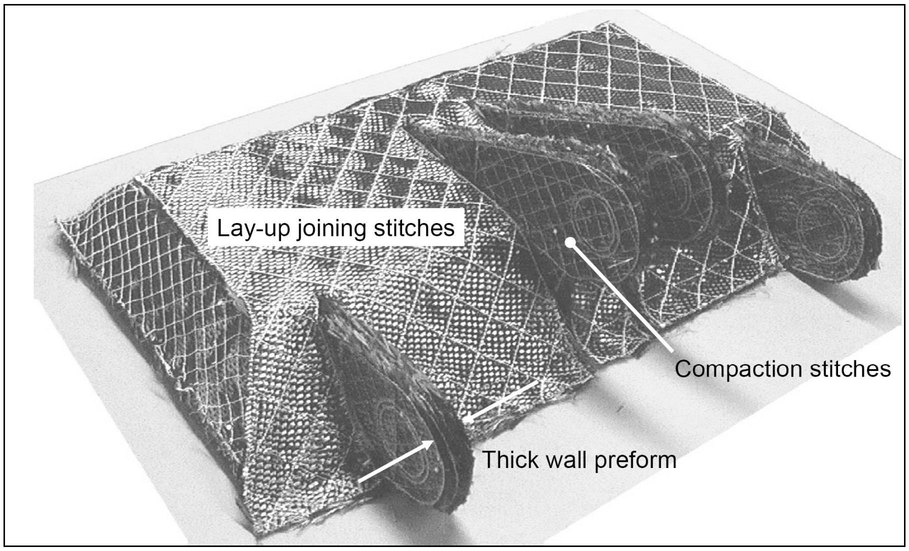


Figure 2.13: Example of net-shape preform [51] (centre fitting spoiler demonstrator for Airbus A330, A340) based on modified lock stitch

To manufacture 3-D net-shape preforms by means of sewing technology, the textile fabric has to undergo various stages of preforming: 2-D preforms, 2-D sub-preforms, and 3-D sub-preforms. Figure 2.12 shows a generalized scheme of the process flow and Figure 2.13 shows sewn ready to impregnate net-shape preform. Due to the number of advantages, the preform sewing process is more and more popular in recent years. Complex preform manufacturing by this method can be inexpensive and simple compared to direct preforming. By means of sewing, impact damage tolerance, delamination resistance to ballistic impact, through-the-thickness tensile strength, tensile modulus, interlaminar fracture toughness, and fatigue resistance can be increased significantly. One of the challenges is that the high speed sewing machines can not stitch very thick composite structures. Furthermore, most of the sewing machines require access to both sides of the preform, curved and complex shape preform needs only robotic controlled machines, and effect of sewing parameters (e.g., stitch density, thread materials, thread linear density, etc.) are not fully understood.

Considering the challenges mentioned, sewing machine manufacturers and researches tried to improve this technology and today most of the industrial grade sewing machines can handle preforms up to 5 m wide and approximately 30 mm of thickness. This step helps for improving the utilization of sewn preforms for various applications in the aerospace, automobile, and classical mechanical engineering component manufacturing. Current status of the sewing machines and the state-of-the-art of preform sewing are explained in following section.

2.3 State-of-the-art of sewn preforms

Various sewing technologies can be used to manufacture sewn multi-textile preforms. The FRPCs developed from such preforms are wide spread and have number of applications [52]. To sew a fibrous preform of exact contour and size, various stitch types have to be introduced into the preform geometry. Application of a specific stitch type for a specific purpose is as critical as employing a sewing technology for manufacturing the FRPCs. The specific distinction has to be made between manufacturing technology, handling oriented sewing, and TTT-reinforcement of the preform structure. The criteria for bringing the seams in FRPC are: each seam type should have a concrete product application, and individual process parameters have to be taken into consideration for consolidation and impregnation. Finally, the influence of preform handling practices on the mechanical characteristics of the product should be kept in mind.

2.3.1 Types of stitches

Number researchers examined the mechanical and rheological characteristics of the sewn preforms and composites in large extent [1, 53, 54]. The knowledge of stitch types and its influence on the FRPC can help to integrate a preform manufacturing chain as a goal. Due to the flexibility and easiness of operations, usually, chain stitch and lock stitch are selected for manufacturing the preforms [55]. The selection of seam type can influences the overall manufacturing concept, which begins with the manufacturing of semi-finished material and ends with the hardening of FRPC product.

For evaluation of the FRPC serviceability, stitch formation parameters play a vital role. Thus, the threads to be introduced into the preform, construction of the fibrous structure, and in-plane and through-the-thickness direction of sewing are the principal parameters required to be taken into account. Different kind of stitches follow dissimilar thread passages during the sewing, therefore, during the consolidation and impregnation process the behavior of the constructed package can be diverse. Common type of stitches used in the composite manufacturing are: modified lock stitch, chain stitch, blind stitch, one-sided stitch (OSS®), and tufting [56 -60].

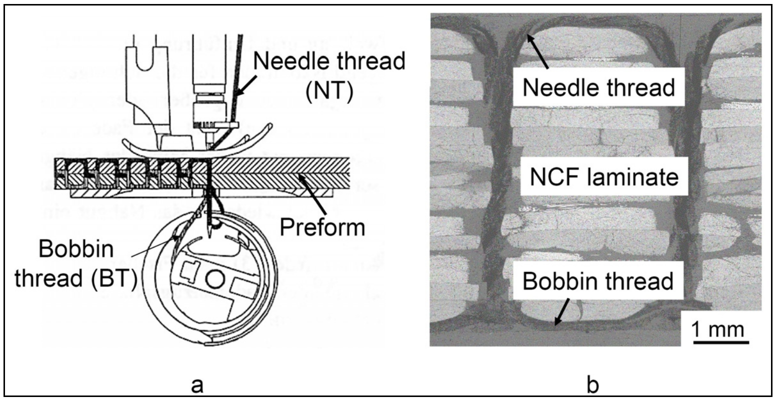


Figure 2.14: a) process of lock stitch formation and b) laminate containing modified lock stitch

Figure 2.13 shows a sewn 3-D net-shape sewn preform based on modified lock stitch and Figure 2.14 shows schematics of lock stitch formation and a micrograph of Glass fiber sewn NCF laminate. The modified lock stitch has advantages in terms of packing of complete lay-up between upper and lower thread and very less restriction on the type of thread to be used. Furthermore, sewing can be performed up to 5000 stitches/min (SPM).

Figure 2.15 shows blind stitch head and an example of sewn preform application: polyester sewn CF preform for bulkhead of A380 airplane. The preform was developed by laying several layers of carbon-fiber fabrics side by side on a table measuring over eight meters in both length and width.

The complete assembly of joined sheets for the rear pressure bulkhead emerges from the sewing machine in the form of a large “carpet”. In the next step, the carpet is rolled up and then rolled out again over a dome shaped mold. To obtain the necessary strength from the carbon composite material, six of these carpets are laid in alternate directions on top of one another and sewn together to form a preform [58].

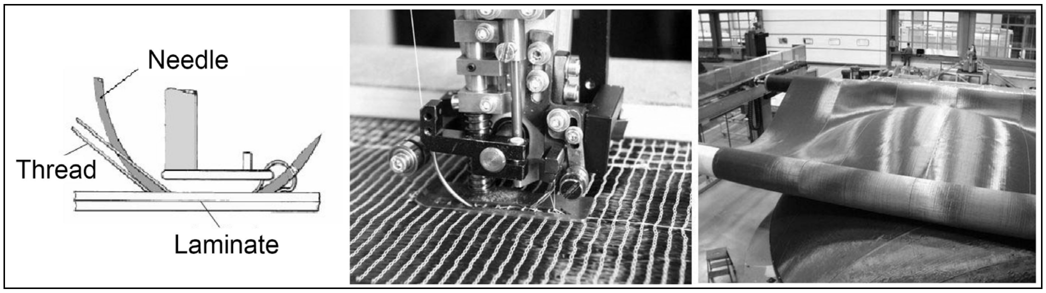


Figure 2.15: Schematics of blind stitch [37], sewing head [39], and CF-PET sewn preform for Airbus A380 bulkhead [58]

2.3.2 Seam types and stitch geometries

The functionality of the seam depends on its position in the stitched preform. For various applications, seams have to behave specifically to fulfill its real application, i.e., 3-D reinforcement or easy to handle preform assemblies. For the preform sewing there are three main seam types, which are generally classified as: fixing and positioning seam, assembly seam, and structural seam [61]. Each seam type is connected with the different type of thread, machine settings, pattern, and speed.

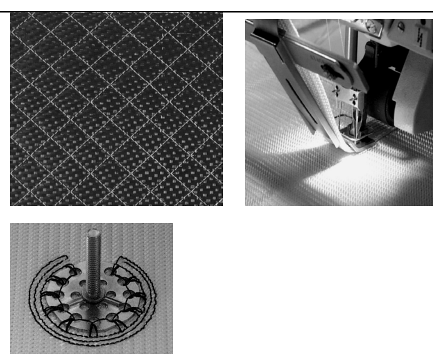
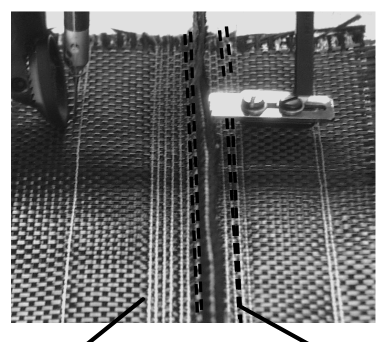
Fixing and positioning seam is generally used for joining 2-D textile reinforcing fabric layers (either mono or multi-textile). It helps positioning the fabric lay-up and blocks the further movement of well aligned reinforcing fibers. Fixation of preform can be done by various kinds of sewing patterns, e.g., stitch rows parallel to the reinforcing fibers (0° or 90°) or crossed pattern (±45°), etc. Commercially available polyester sewing threads are suitable for this kind of seams, which can be effectively used than the other high performance threads.

Apart from joining various textiles in a single lay-up, integration of non textile components, such as metallic inserts, into the main structure is also a function of this type of seam. Furthermore, positioning of individual rovings or narrow fabrics at the pre-defined high stress locations is one of the advantageous features of this seam type.

Assembly seam helps to mount 2-D sub-preform structures, which are manufactured in the first stage of lay-up positioning, and forms 3-D net-shape preform assembly. The assembly seams are used to join the preforms in and out-of the plane, thus, this kind of seam is useful to manufacture a ready to impregnate dry preform geometry. Multi-directional and multi-axial positioning of stitches is a base for this kind of seams. In general for 3-D sewing, a robotic controlled sewing machine is helpful for such seams but manual operated machines can also serve this purpose. The number of seams to be placed to assemble preforms is much less than the fixing and positioning seams. Therefore, for assembling the preforms, either polyester thread or high performance threads like Kevlar®, Nomex®, or glass can also be used.

A structural seam is used for improving structural properties and functionality of the FRPC laminate. TTT reinforcement at the particular zone of laminate is a function of this seam. Structural seams are laid either after the fixing of 2-D preforms or after the assembly of complete 3-D preform. Depending on the requirement, stitches are laid in various axes. Machines used for such seams are either robotic controlled or semi automatic ones, which operates relatively slowly but with precision and accuracy. For this kind of seams, high performance fibers like carbon fiber, glass, aramid, or Zylon (poly p-phenylen-2,6-benzobisoxazol, PBO) are more advantageous, which can later contribute in the laminate structural properties. Table 2.2 explains the required machine parameters to be set for different type of seams.

Table 2.2: Different seam types and required machine settings

			
Seam type	Preforming seam	Assembly seam	Structural seam (Z)
Thread material	Polyester	Polyester, aramid	Aramid, glass, carbon, etc.
Applied thread tension	High to medium	High	High
Stitch density	Medium	Low	High

Stitch formation inside the reinforcing preform structure can be possible by means of various stitch types, e.g., lock stitch, blind stitch, one-sided stitch, tufting, etc. According to the specific application of individual seam, the stitch type has to be selected. Combination of the stitches and the seams can be the best option to optimize preform manufacturing and the FRPC quality and properties [60].

2.3.3 Overview of the worldwide sewing techniques

In recent decade there have been various developments in the sewing machines to manufacture dry textile preforms. The majority of developments are based on the manufacturing of big structures and free-axis sewing. Following are some of the recently developed sewing techniques:

National aeronautics and space administration (NASA) sewing machine

Assembling the carbon fabric preforms with closely spaced TTT sewing which can provide essential reinforcement for damage tolerance was the main objective of NASA. The process of sewing was also used to incorporate the various elements, e.g., wing skin, stiffeners, ribs, and spars, into an integral structure that would eliminate thousands of mechanical fasteners. The studies showed that sewing had the potential for cost-effective manufacturing, however, the critical need was a machine capable of sewing large wing preforms at higher speeds [62].

Figure 2.16: ASM developed by Boeing and NASA Langley research centre (LARC) [62]

A multi-needle quilting machine and in the later stage a single-needle gantry machine was used for through-the-thick carbon fabric sewing trials. Both the machines were not suitable for large and complex contoured wing structures, therefore, NASA and Boeing developed a larger machine capable of sewing entire wing covers for commercial transport aircraft [63]. The outcome of this is a high-speed and multi-needle machine that is known as the Advanced Sewing Machine (ASM) (Figure 2.16). The ASM is an integral part of the stitched and Resin Film Infusion (RFI) based composite manufacturing process.

In 1994, a computer-controlled single-needle sewing machine capable of sewing dry high performance textile materials (such as carbon and glass) was designed and built for the Materials Division at Langley. The sewing machine was capable of sewing an area of 1.2 m wide and 1.8 m long with thicknesses more than 38 mm using a lock stitch and programming sewing in any direction (including curves) within the sewing area. The machine was capable of sewing with a wide variety of needle and bobbin threads, such as polyester, nylon, Kevlar®, and carbon. A wide variety of preform sizes were fabricated and delivered to McDonnell Douglas for RFI processing to produce test specimens for evaluation at NASA Langley. Boeing was seriously considering using this technology in the next generation of aircraft [64].

Sewing machine at Eurocopter Deutschland GmbH

This is a Keilmann Sondermaschinenbau Lorch GmbH (KSL) series sewing machine consists of a computer program controlled sewing head which rotates in 360° direction and in x and y direction along the fixed fabric width and length, facilitating multi-directional contour sewing. The sewing head is suitable for lock stitch and modified lock stitch. From the fabric creel, material is continuously supplied for the sewing operation. During the sewing process, the material is clamped firmly and stays stationary throughout the operation and with the help of the rotary and movable sewing unit different geometries can be stitched.

The machine is based on the computer numeric control (CNC) operation [65, 66]. Figure 2.17 shows complete machine with fabric rollers, sewing head, and preform take-up table and, sewing head with CCD camera for monitoring the process. During sewing process, to avoid the sagging of textile fabric material, number of bands support the fabric lay-up from the beneath along the fabric width and throughout the sewing field. Stitched preforms can be possible to be transported to the cutting facility or can be take up separately and cut by using punching tools.

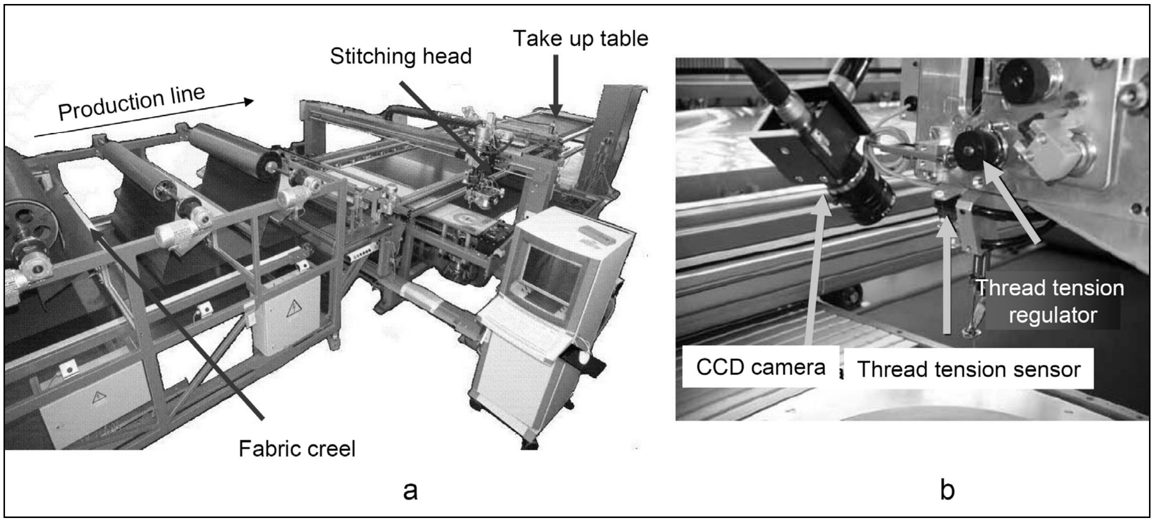


Figure 2.17: a) Sewing facility at Eurocopter Deutschland GmbH, Germany; b) sewing head [66]

Institut für Verbundwerkstoffe GmbH, Kaiserslautern, Germany (IVW) lay-up-sew-cut machine

Sewing machine from Parker Hannifin GmbH & Co. KG and cutting machine from Assyst Bullmer Spezialmaschinen GmbH & Co. KG were combined to develop a sew-cut machine. The machine used for preform sewing is linked to the RTM operations, thus, the preform production comprises different stages. The machine consists of back rolls to mount the reinforcing semi-finished material, e.g., NCF, woven fabrics made up of glass or carbon fibers. Figure 2.18a shows the set-up of the machine and Figure 2.18b shows schematics of complete line.

For a handling-free process, the reinforcing material is transferred to the sewing unit continuously using lateral gripper chains. The machine consists of one sewing head which moves in x and y direction, facilitating multi-directional contour sewing. The sewing head is suitable for lock stitch and modified lock stitch with maximum operating speed of 5000 SPM. During the process, the material stays stationary and the sewing unit moves along the tow axis. Sewing field is approx. 2.8 m x 2.8 m in size which can also used to manufacture different small preforms at the same time [67, 68].

After the sewing operations are finished, the sewn lay-up is automatically transported to the cutting unit by the same lateral gripper chains. At the cutting zone, the individual preforms cut to the final shape. The computer images provide geometries of stitches and cutting lines. Furthermore, the camera attached to the system monitors the cutting patterns and make sure that the cutting operation is precise along the seam line. To avoid the disturbance in shape of the sewn preform and textile material, the material is kept in place by partial vacuum that acts over the full area of cutting table. The preforms from the take-up station can be used directly for the part manufacturing or can be processed further for 3-D net-shape preform manufacturing.

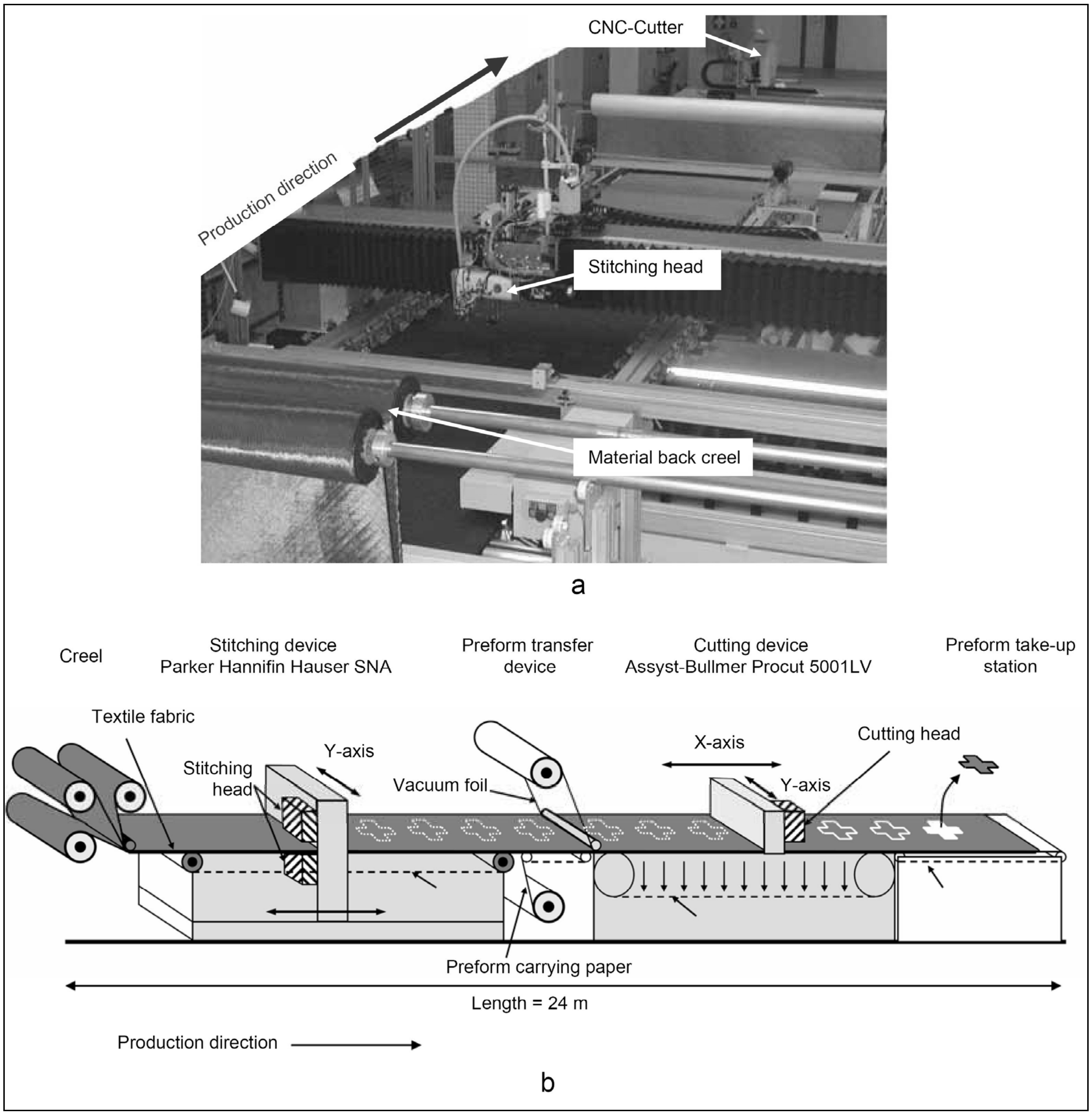
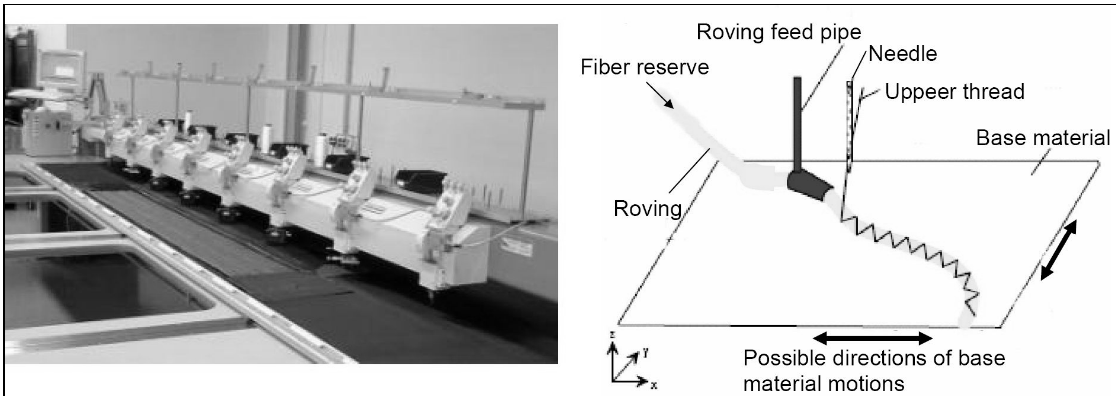


Figure 2.18: IVW lay-up-sew-cut machine modified to sew reinforcing fabrics: a) actual machine; b) schematic diagram [69]

Composite technology center (CTC), Stade - tailored fiber placement machine

The tailored fiber placement (TFP) is used for the deposition of dry fiber rovings on a sewing base. The reinforcement structure is produced by the lay-up of a single roving. This roving is fixed by means of seams to a base material. The base material can be a 2-D-textile such as a woven fabric or a matrix-compatible foil for thermoplastic composites. During the process, the sewing unit is stationary and the base material with frame is moved using numerical control. For economical manufacturing, in general, up to 30 working units and a high sewing speed can be used [70-72].



a b

Figure 2.19: a) TFP machine and b) schematics of working principle [72]

The machine consists of 8 sewing heads, work envelope per sewing head is 1200 mm x 700 mm and different types of stitches are possible, e.g., standard sewing, taping, different zigzag pendulum sewing patterns, and coiling. Thread tension is automatically set with individually adjustable thread tensioners for the different sewing patterns. Programmed patterns can be repeated up to 99 times, enabling operations such as mirroring, rotations, and displacements. Figure 2.19 shows the TFP machine and schematics of the fiber placement principle.

The Applications of Tailored Fiber Placement Technology demonstrate the unique possibilities to adapt the fiber structure in terms of shape, thickness variation, and fiber orientation. The design of the structures can be oriented on the principle stress directions, which eliminates the shear stresses and is well suited to avoid stiffness dominated flaws. Furthermore, for other requirements, tailoring can be useful to enhance the exploitation of the materials anisotropic properties [73].

Robot-controlled sewing machines

Robot-controlled sewing machine at CTC, Stade consists of an industrial robot from KUKA (KR 125) with linear unit (KL 1500). 3 stitching heads from KSL (double lock stitch, blind stitch, and tufting head).

The sewing technology is applied for the manufacturing of complex textile structures (preforms) and for the improvement of the structural properties of consolidated composites. The machine is a 6-axis robot from KUKA (KR 125) with repeatability within 0.2 mm. In order to enlarge its work envelope, the robot is attached to a gantry and can be moved linearly on a guide rail (KL 1500) so that an overall volume of 5000 x 3500 x 1500 mm can be attained. By using a fast-changing device, three different stitching heads and a laser measuring head can be attached. The latter is used to measure the deposition area. It can be automatically connected to the robot. The stitching heads are two single-sided stitching heads (blind stitch and tufting head) and a double-lock stitching head for which the part needs to be accessible from both sides [74].

A robotic sewing machine at Institut für Flugzeugbau (IFB), Stuttgart has equipped with a KUKA robot and several stitching heads for various sewing operations [75].

Robotic controlled sewing machine by KSL

KSL has made a combination of 2-D and 3-D stitching unit for the production of large composite components for aerospace industry. A linked robot stitching cell and a portal stitching unit with turning stitching head allow a big variety of 2-D and 3-D seam applications. Figure 2.20 shows stitching unit developed by KSL.

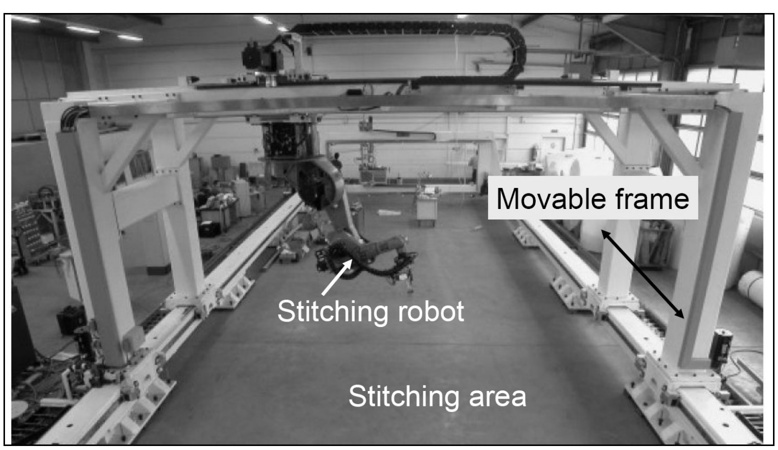


Figure 2.20: KSL combined robotic controlled and CNC machine [76]

IFB, Stuttgart has a CNC controlled KSL sewing machine with sickle-shaped needle. Computerized program can help to reduce the wastage of reinforcing material [75].

Single sided sewing machines

Due to inaccessible side of the complex preform for double sided stitching, like, double lock stitch or chain stitch, a concept of single sided stitching came up. One-sided stitch by Institut für Textiltechnik, Aachen (ITA) and Altin GmbH, Blind stitch and tufting machines of KSL, tufting heads from Altin Nähtechnik GmbH (Altin), etc. developed verity of concepts for stitching without accessing other side of the preform.

Altin one-sided sewing (OSS®) machine

The technology of sewing is not efficiently applied in the majority of cases, mostly due to the large dimensions and the three-dimensional structure of the FRPC component. To overcome the major limitations, Altin Nähtechnik has developed a robotic controlled sewing technology [77, 78].

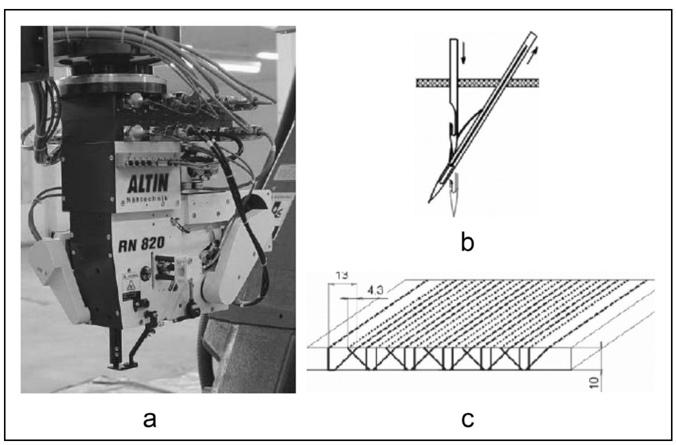


Figure 2.21: a) Altin OSS® sewing head, b) needle pattern, and c) schematics of stitched pattern

The principle of the simple chain stitch with the manipulation of sewing thread by two sewing tools is a conventional needle and a catcher. Unlike other sewing methods the interlocking of the sewing thread on the work piece takes place on the top side (Figure 2.21).

One-sided stitching concept by ITA:

The principle of ITA stitching head is also consists of two sewing needles. Both the needles penetrate from the top of the preform with the sewing thread. The stitch geometry formed by these needles is shown in Figure 2.22. The basic differences between ITA and Altin sewing technique are the threads involved in a stitch (one thread in Altin technique and two threads in ITA technique) and stitch formation phenomenon. Figure 2.22 also shows the geometry of Altin and ITA stitches.

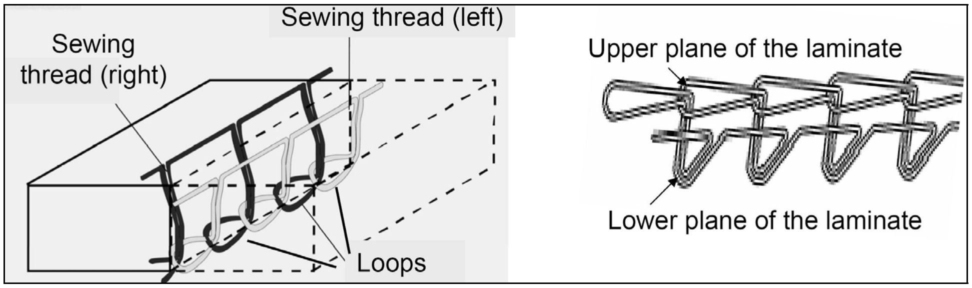


Figure 2.22: (l) ITA concept of one sided stitching [79] and (r) Altin concept of stitching

KSL Blind stitch machine:

Blind stitch seam is formed with only single thread, which brought into the material by one curved needle from the top side of the material. It is a classical stitching technique with advantages of variety of adjustable penetration depth depending on the material thickness and typical advantages of single sided stitching: bottom thread is not required and access to the preform from one side only. This technique is used for 2-D and 3-D preforming applications, in general for positioning and assembly seams. KSL KL 151 robotic control stitching head with blind stitch attachment is shown in Figure 2.23.

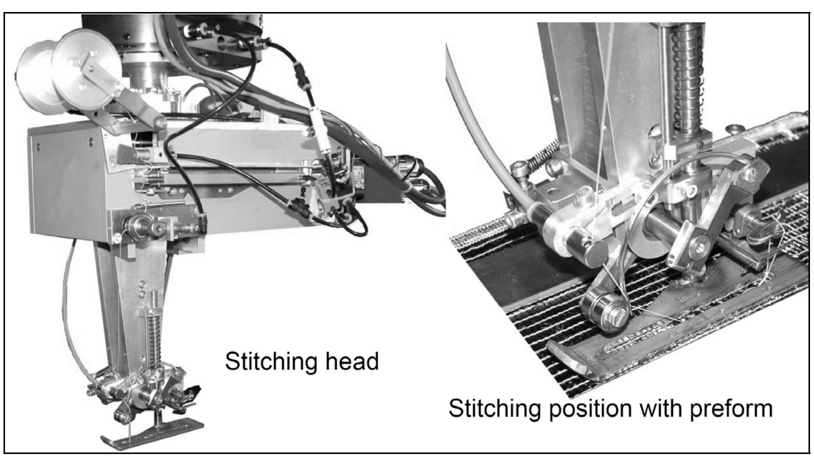


Figure 2.23: Blind stitch head and stitching position [76]

Tufting machines

Tufting represents a very novel approach to localized TTT reinforcement in structures for the dry preform and liquid resin injection manufacturing route. It is intended to reduce delamination by modifying the fiber and resin architecture. A single needle takes a yarn through the fabric layers and returns back along the same trajectory, leaving a loop of thread on the back side of the plies. The tufting stitch is never locked and only remains in the position because of frictional forces acting on it. This leads to a virtually tension free structure and, in turn, to less waviness in the fabric and fewer challenges during the subsequent resin injection.

The robot assisted tufting represents an ideal approach for localized reinforcement because of the possibility of rapid processing of complex three-dimensional shapes. Automation implies high reproducibility, in less time, with virtually no manual handling of the fabric before resin injection. Figure 2.24 shows a “tufting head” for operation on conventional CNC machines developed by KSL [76] and Deutsches Zentrum für Luft- und Raumfahrt eV (DLR), Institute of Structural Mechanics, Braunschweig.

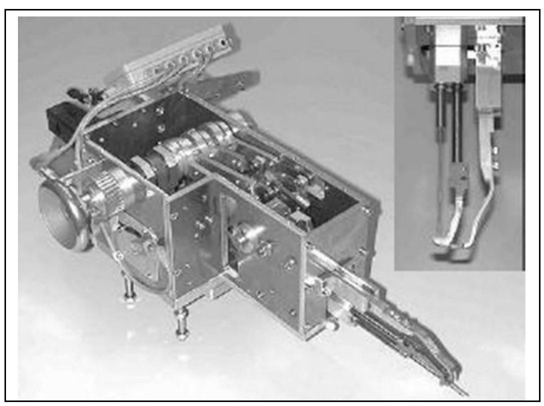


Figure 2.24: Tufting head developed by KSL and DLR [27]

ALTIN sewing head is also used for tufting the reinforcing material. The insertion of load carrying threads in Z-direction in straight or angular fashion is the main target of their tufting technology. Figure 2.25 shows Altin tufting head and schematic of tufted sections. The advantage of tufting is the low thread tension under which the thread is inserted. This results in a reduction of sewing effects on the in-plane properties of FRPCs.

Tufting can also join semi-finished parts together, making the reinforcing material easier to handle. It is a one-side access technique and then not only requires less tooling in comparison to standard sewing, but also makes possible:

- tufting on the mold (partial, Figure 2.25)
- processing complex and 3-D shaped pre-forms
- processing unlimited thickness by subsequent lay-ups
- choosing needle penetration angle.

As far as tufting process in aerospace industry is concerned, European Aeronautic Defense and Space Company (EADS) Deutschland GmbH has this facility to do research at their laboratory for the localized 3-D sewing of reinforcing material [58].

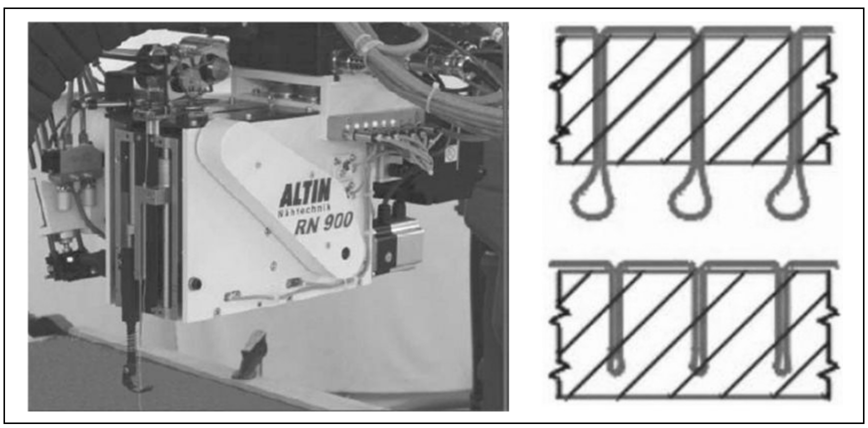


Figure 2.25: Tufting head and tufted threads inside the laminate

It has been explained in the literature that the reinforcing of complex CFRP structures by means of robotic stitching leads to a significant increase of resistance and energy absorption of the material. These results-especially the energy absorption– gives important information about the toughness of the connection area [56].

All the sewing machines are suitable for various sewing parameters. The machine settings required for the specific operation can flexibly be changed according to the sewing parameters, for instance, type of sewing thread. In the following chapter, essential properties of sewing threads for the preform manufacturing are explained in detail. Furthermore, types of sewing thread suitable for preforming are also discussed.

3 Investigations of sewing threads for preform manufacturing

In FRPCs based on sewn preforms, the laminate performance depends on the quality of seam structure and seam efficiency. Sewing threads are also important in the manufacturing of net-shape preforms and LCM processes. The seam efficiency is influenced primarily by the type and quality of sewing thread used in preform sewing. Apart from this, there are number of factors which affect the FRPC structure and the majority of them are shown in Figure 3.1. The selection of sewing thread for preforming is based on its physical properties and application areas.

Although, the sewing operation is one of the most important stage in preform manufacturing [80], a very limited work is reported to relate the sewing process parameters and the mechanical properties of the composite laminates manufactured from sewn preforms. Therefore, in this chapter, detailed studies on essential properties of sewing threads and their effect on preforming are discussed. Selection of sewing thread based on the preforming applications, thread properties, and suitability for sewing machines are explained in detail.

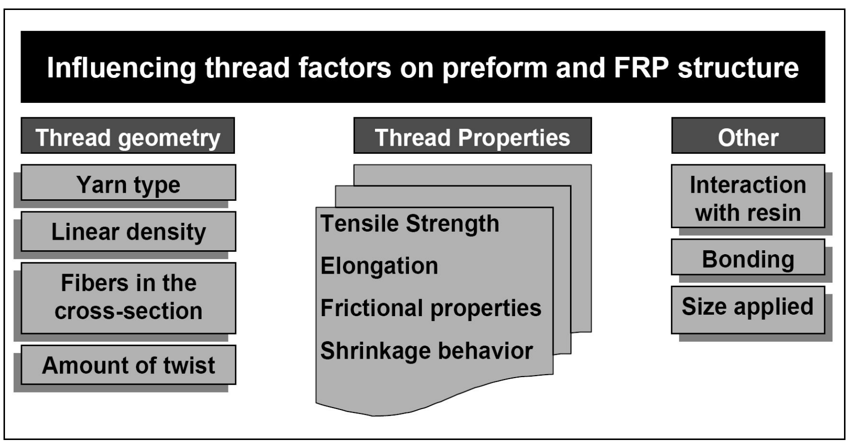


Figure 3.1: Properties of sewing thread influencing on the FRPC structure

Preform manufacturing using sewing threads poses numerous challenges such as, frequent thread breakages, poor knot formation due to thread snarling, widened stitch-holes, etc. Furthermore, improper selection of thread may affect the microstructure of a laminate, for instance, void formation due to degassing of thread finish, and properties of the laminates. Various studies reported in the literature and some preliminary experiments performed at IVW show that the sewing process can be optimized by selecting the proper sewing parameters. The basic properties that a sewing thread should posses are discussed in detail in following section.

3.1 Essential properties of sewing threads

Industrial sewing techniques make specific and often very exacting demands on the threads involved in the sewing process. The sewability of threads is important parameter which has a very profound effect on seam quality and production costs. The sewing and the seam performance of a sewing thread are largely influenced by various factors like material to be sewn, the sewing technique, and the end-use for which the sewn material is intended. These requirements can be defined as:

- ability of sewing threads to meet the functional requirements of producing desired seam effectively
- ability of sewing threads to provide the desired performance and serviceability in the seam
- the costs associated with the sewing thread and producing the desired seam

Based on these requirements, various important properties are discussed below that are essential for a sewing thread qualification for preforming:

Threading: Needle thread (NT) must pass through the small needle-eye; consequently the thread must be uniform, knot-free, non-torque, and fault free.

Applied finish: The spin-finish and lubricant applied on the sewing thread are basically aimed for its better performance during sewing. However, it influences adversely on the resin impregnation quality [81, 82]. An epoxy-matrix-compatible sizing should be applied on the thread material and the thread must be free from silicon substances. Figure 3.2 shows void formation around the sewing thread and inside the laminate and, the unimpregnated polyester filaments.

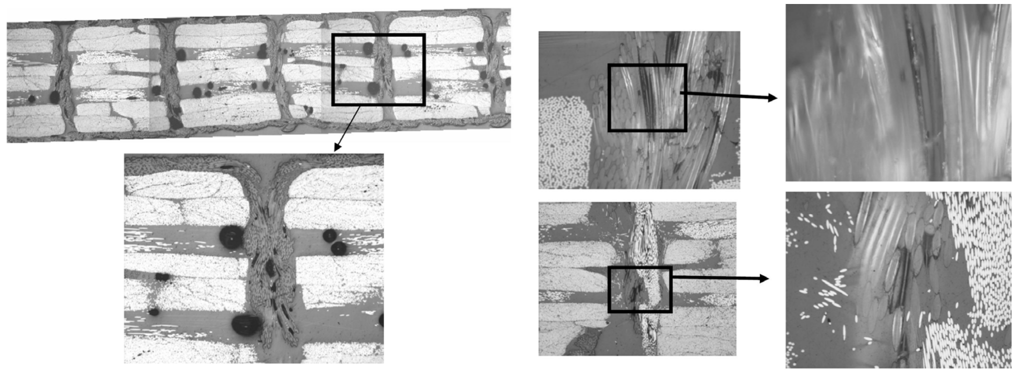


Figure 3.2: Caused laminate defects due to thread spin-finish

Strength: During high speed sewing process, the needle thread is subjected to repeated tensile stresses at very high rates. The thread also comes under the influence of heat, bending, pressure, torsion, and wear. The value of these stresses depends on the sewing speed, machine settings, and the thread used. The stresses created within the thread have a negative influence on the processing and functional characteristics of the thread and there is a significant reduction in the thread strength after sewing [83].

The function of the dynamic and thermal loading of the thread is influenced by the thread frictional properties, thread tensioning during sewing, needle size, stitch length, and number of fabric layers in the seam. The thread should, therefore, possess adequate strength and elongation for satisfactory performance during the sewing process and in the seam [83].

Extension-at-break: For steady fault-free performance during sewing, moderate extension-at-break in the case of polymeric threads and low extension-at-break in the case of high performance threads (e.g. carbon, glass, etc.) are usually preferred. Needle thread with different extension-at-break has been found to behave quite differently during stitch formation.

Elasticity: The elasticity of the sewing thread must be uniform along its length in order to enable equal length of stitches to be formed, but need not to be matched with the elasticity of the fabric being sewn. Too high elasticity cause springy action of the thread after the cutting. There are some special threads used in preform sewing process having high elongation. To work with such a critical thread, machine modifications are necessary, for instance, a small suction system needs to be attached near the needle (Figure 3.3) to overcome the spring action of thread and to improve the gripping capacity of the thread clamp.

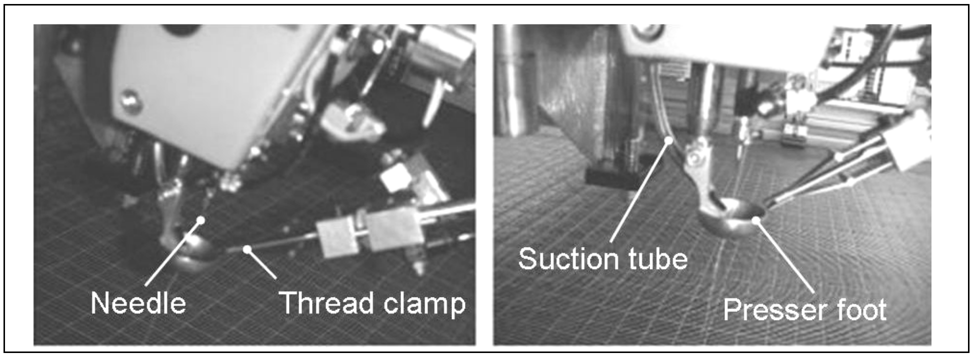


Figure 3.3: Suction attachment for holding thread end just after the cutting.

Frictional properties: The forces that are developed in the sewing thread are mostly due to the friction between the thread and machine parts, the most severe action taking place between the thread and needle, and the thread and fabric being sewn. The static and dynamic friction is required to be restricted to avoid lack of thread control during sewing. Furthermore, static friction values are necessary to allow the stitches to lock and prevent "run-back" of seams. Spun threads are particularly good in this aspect when compared with filament thread.

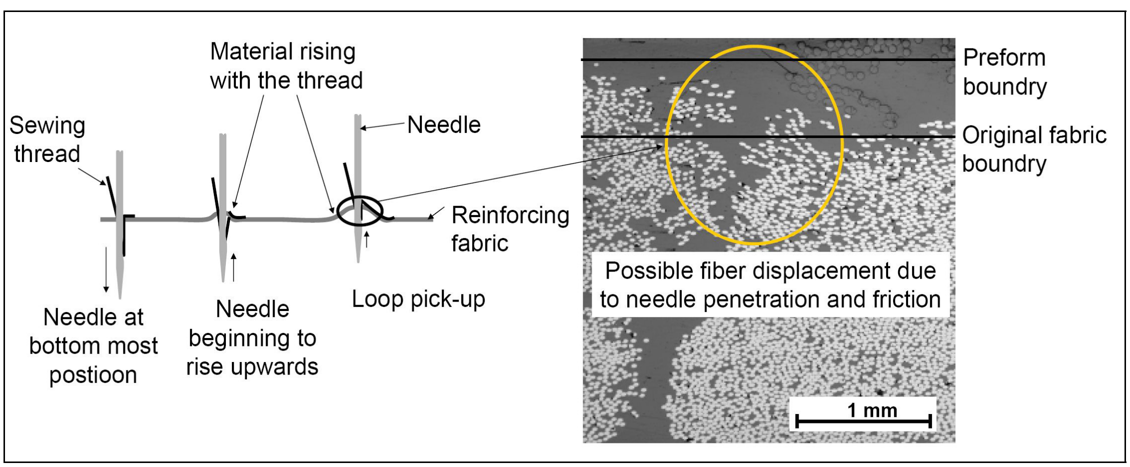


Figure 3.4: Influence of thread to fabric friction on reinforcing fiber displacement

The frictional properties are definitely affected by lubrication, therefore, the factors that influence the frictional properties are:

- uniform application of lubricating agents
- adhesion of the finishing agents on the thread.

The quantity and quality of applied finish are very important for thread surface characteristics. Influence of thread frictional properties and interaction with the needle on reinforcing material is shown in Figure 3.4.

Abrasion resistance: Good abrasion resistance is essential for improved sewing performance. During sewing, especially when the stitch is being set, the thread is under tension condition. The thread must be resilient enough to return to shape after the distortions, and then must maintain its physical properties to provide good performance in the seam after the sewing process is completed. Amongst all types of sewing threads, polyester threads offer the best resistance to abrasion.

Thread elasticity, strength, and frictional properties affect on the fiber displacement and ellipse formation. Figure 3.5 shows formed ellipse like fiber-spread in 0° and 90° direction in the reinforcing material.

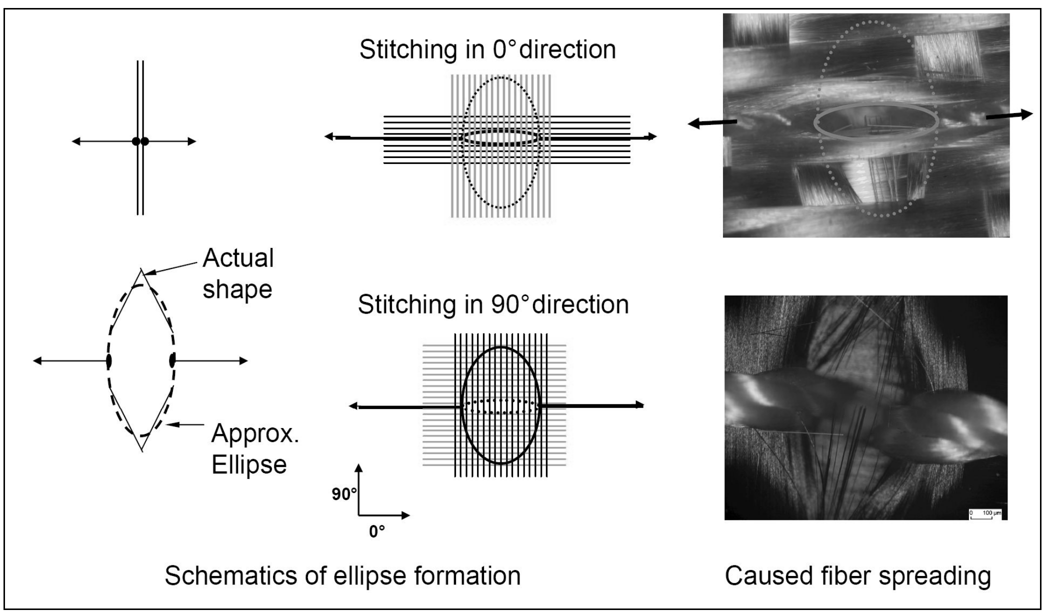


Figure 3.5: Phenomenon of ellipse formation in the dry preform

Heat resistance: Good resistance to heat is a very important requirement of a sewing thread. The temperature reached by a sewing needle during sewing is very much depends on the nature of the fabric to be sewn (density, thickness, and spin finish), speed of the sewing machine, type of needle used (size, shape, surface finish), and sizing or finish applied on the sewing thread. The needle temperature is especially critical for sewing threads of low melting thermoplastic fibers, because they may exceed their melting temperature (T_m). Needle heating causes sewing thread breakage, cross-thread, skipped stitches, seam damage, and physical damage to the needle.

The sewing thread influences the needle temperature significantly. Thread movement through the needle reduces the needle temperature by an average of 21-45 %. However, the amount of reduction depends on the sewing condition and structure, fineness, and composition of a sewing thread.

Direction of twist: The final direction of twist insertion is important to enable the stitch forming mechanism of the sewing machine. It is also depends on the position of the bobbin, either on the left side or right side of the machine. Most of the sewing machines require threads with Z-twist, but there are some studies which reported better sewing with S-twist also [84]. Figure 3.6 shows untwisting of thread during sewing operation. Proper combination of needle and thread twist may reduce sewing defects and unnecessary machine stoppages.

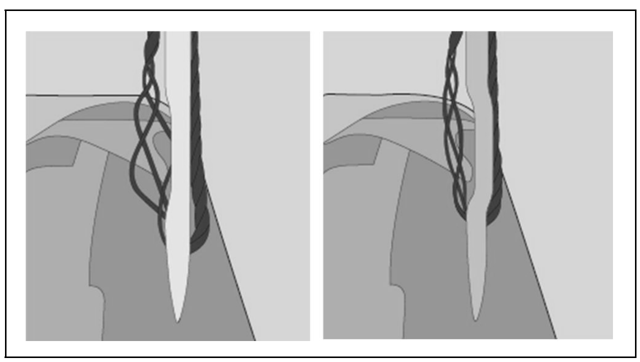


Figure 3.6: Combination of needle type used and thread twist [85]: (l) extreme untwist, (r) tolerable untwist

Shrinkage behavior: During the hot resin injection the required thread shrinkage should be low. Shrinkage due to fiber swelling causes seams to pucker, which widens the stitch-hole size and thus, increases the resin rich zones. Typically, polymeric-synthetic threads owing to their relatively lower melting temperatures show this type of behavior. Furthermore, they are liable to residual shrinkage if the unsuitable manufacturing processes are employed. However, lower shrinkage is expected for sewing threads with high performance materials. Thermal shrinkage can be reduced or eliminated by using high temperature setting of polymeric threads, which stabilizes the thread at the temperature above the RTM process and the curing cycles.

Special features: The preform contour sewn by means of fixing seam needs to cut in the later stages. On the high speed-programmable cutting machines, the seams are detected by means of a black-light active camera. The only traces that the camera can follow are the stitches .Thus, the thread used for the sewing required to be optically bright which helps in detecting the seam. Generally this feature is applicable for polyester threads and not for high performance threads. So polyester thread needs to be treated with optical brightening agent which should not affect RTM processes and laminate quality.

Matrix soluble threads are in a development phase which can be the best alternative to reduce sewing defects and improve FRPC laminate quality and properties. Such types of threads need special types of matrix systems containing chemical groups which are responsible for dissolution of matrix soluble thread material and distribute inside the laminate. Figure 3.7 shows dissolution phenomenon of an epoxy soluble thermoplastic polymer (TP) thread with dispersion of thread polymer into the matrix.

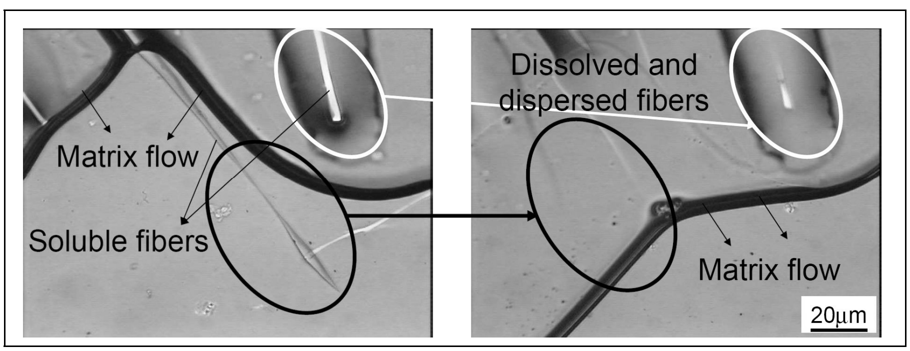


Figure 3.7: Phenomenon of fiber dissolution: (l) before dissolution, (r) after dissolution

Within this category of special threads, the low melting point polymeric threads (PET or polyamide, PA) can also be used. In general, such a multifilament thread melts below 120 °C, the typical temperature of resin injection and first curing cycle of the laminate. Such threads are commonly used in melt-bonded nonwoven fabric manufacturing [86]. Preforms manufactured using this type of threads may be used as a substitute for bindered fabric.

Based on the thread requirements, the overall effect of selection of sewing thread on FRPC quality is shown in the Figure 3.8. Preforming issues, especially the sewing thread factors affecting the laminate quality are highlighted. If the chemical properties of threads are improved, the only major factor for selection of suitable thread is the physical structure. The thread elongation properties show the extensive impact on laminate in terms of fiber misplacements, localized high fiber volume fraction, and resin reach areas.

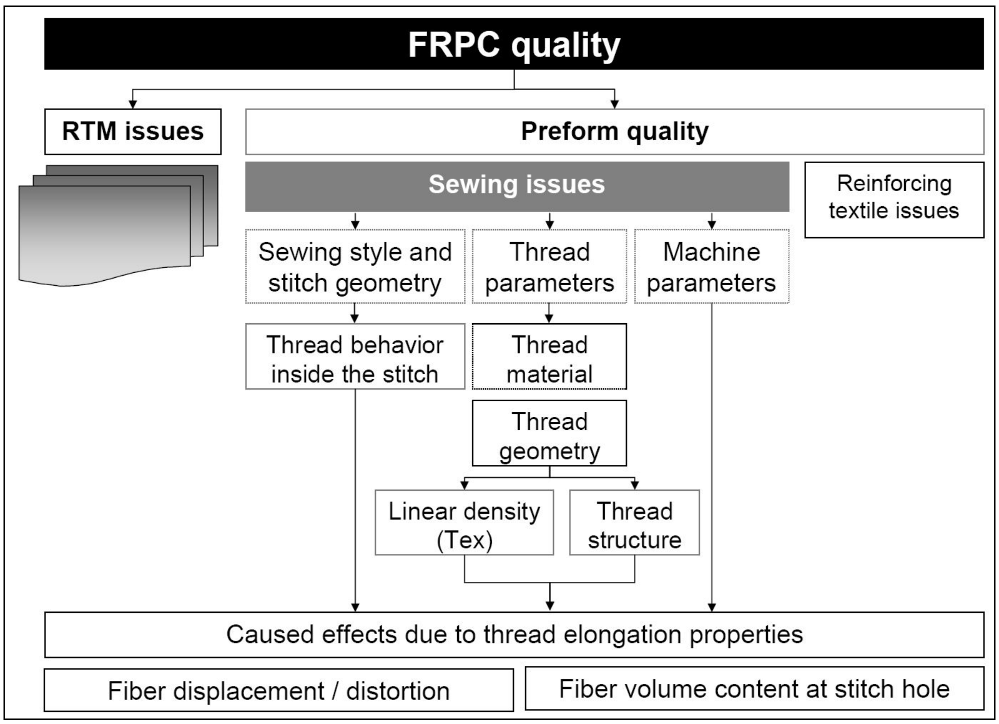


Figure 3.8: Thread properties influencing on FRPC quality

3.2 Types of sewing threads

Threads are manufactured from textile yarns, which are made directly as man-made continuous filaments or spun from the staple fibers. Sewing threads can either be a single yarn or multi-fold yarns or ply yarns. Table 3.1 shows types of sewing threads suitable for specific sewing element.

Short fiber threads: These types of threads are manufactured by using staple fibers with a length of 25-80 mm and spun on the conventional spinning machines.

a) Spun synthetic threads: Usually polyester fibers are used for these threads with staple length of 25-78 mm. Special machines are used for processing and generally higher strength is achieved.

The high-speed sewing machines, which are imposing very high strains on the threads, require sewing thread of high toughness for satisfactory performance. Synthetic fibers have very high strength and durability; however the thermoplastic nature of these fibers makes them susceptible to change in their properties when they are heated either during sewing or in subsequent processing. Stabilization treatment at suitable temperature and stretch during manufacture is therefore essential. Special finishes are also used to improve the threads gliding and cooling properties.

Continuous filament threads: The name itself suggests the type of filament structure, continuous or endless filaments; and that are explained in subsequent paragraphs in detail according to the structure. Figure 3.9 shows the type of polyester threads useful in preform manufacturing.

a) Twisted multifilament threads: Plied or corded threads are used as continuous filament threads. Carbon [87], glass, Kevlar®, Nomex®, and polyester are the typical multifilament threads used in the composite manufacturing processes. Toray carbon fiber thread (T900-2ply) is a commercial twisted thread used for sewing.

Very fine polyester threads are produced from a single ply of multifilament yarn. These yarns are suitably twisted and then treated with a light bonding finish - just sufficient to consolidate the individual filaments without stiffening the final product. As far as 3-D structural reinforcement is concerned, the threads like carbon, glass, etc. should be thick (70 -150 tex) and must have low to medium twist only.

b) Textured threads: Texturing is a general term to describe modifications of the appearance and surface characteristics of flat synthetic filament yarns obtained by various means such as false twisting, air jet, stuffer box, etc. Textured threads have a soft handle and are primarily used as bobbin-threads, where a particularly soft seam is required. Because of its bulky and high elongation properties, this thread is much suitable in the fixing seams where the seam defects needs to be minimized, for instance the stitch-holes caused due to thread rigidity can be closed [84].

c) Monofilament thread: It is not a conventional thread, it comprises only a single filament and suitably lubricated. Monofilaments are produced by melt spinning (like the continuous multifilament yarns), but the diameter of the filament is 2-10 times larger than that of conventional filaments (typically 1-3 tex). These types of threads are normally used as a bobbin-thread, which stays straight at the bottom of the laminate. Because of its rigidity the monofilament threads are not suitable as a needle-thread.

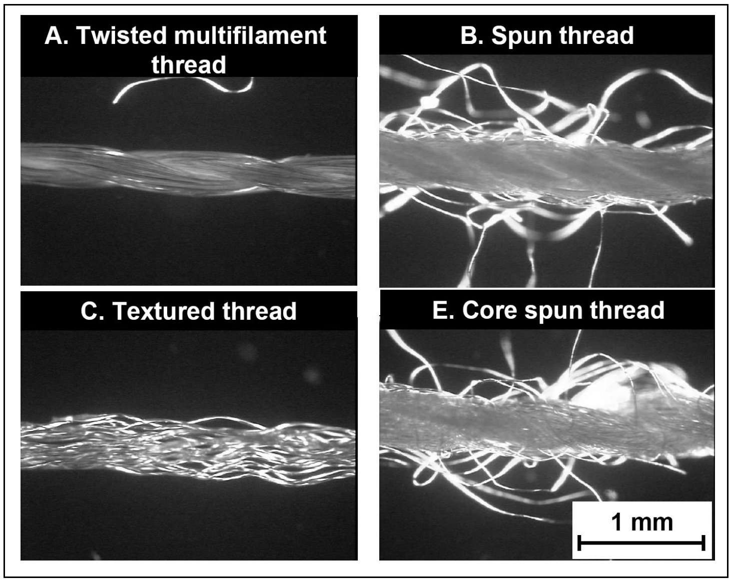


Figure 3.9: Polyester threads available for preform manufacturing

Hybrid threads

a) Core spun thread: Can be used for achieving optimum strength to fineness ratio of continuous filament threads together with the sewing performance and surface characteristics of spun fiber threads. The core filament thread is covered and protected by staple fibers. The strength is provided by the core filaments and the heat resistance of the surface fibers permits high sewing speed. The core spun threads can be manufactured in two ways, a) same material at core and on the sheath (e.g., polyester/polyester thread), b) hybrid thread, with high performance filaments as a core and commodity fibers on the surface (e.g., carbon filaments in the core and polyester fibers as a coating). If necessary, these composite yarns being then twisted to form two or multiply threads. In this type of thread binder material has to be used for the fixation of surface fibers on the core filaments. This might be a cause of concern if the binder material is not compatible with matrix material.

b) Core-sheath threads: The high performance reinforcing material, for instance the carbon fibers (CF) have number of drawbacks which restricts its use as a sewing thread. One of the major disadvantages of carbon roving is poor knot strength, which can be eliminated by making hybrid construction. Core-sheath constructions can be possible in three different ways, e.g., based on the crochet technology (IVW CF-thread [88, 89]), CF thread wrapped by means of the polyester filaments, and based on braiding technology (Schappe thread [90]). These threads are proved to be better at high speed sewing technologies.

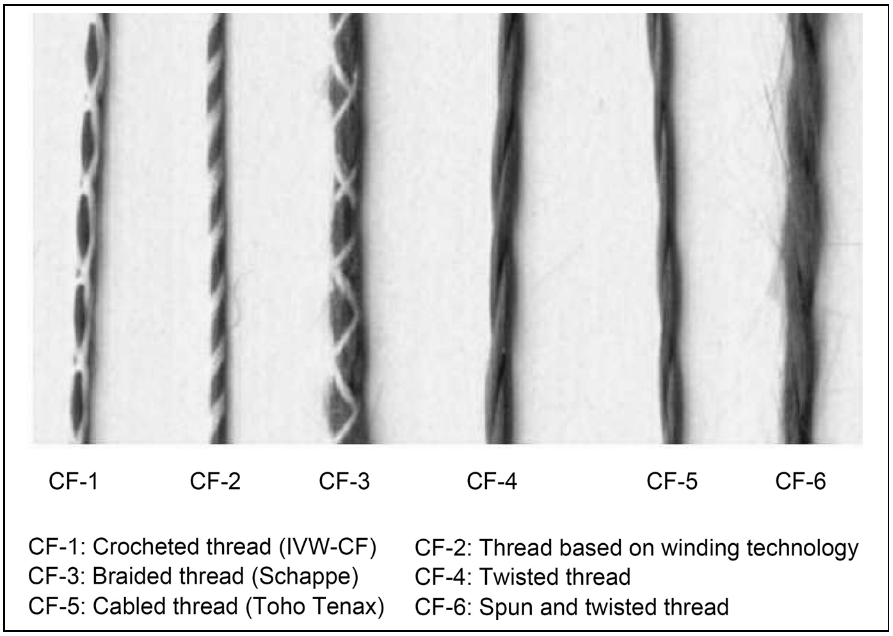


Figure 3.10: Types of carbon fiber sewing threads

Figure 3.10 shows different types of carbon fiber threads including twisted, spun, and cabled threads. Generally a pure carbon thread creates enormous friction between needle eye and thread, which causes fluff accumulation, blocking of some machine parts, and thread breakages (Figure 3.11). Thus, hybrid threads are more suitable for the conventional sewing operations. Spun carbon fiber threads have further challenges of threading and accumulation of short fibers around the needle eye.

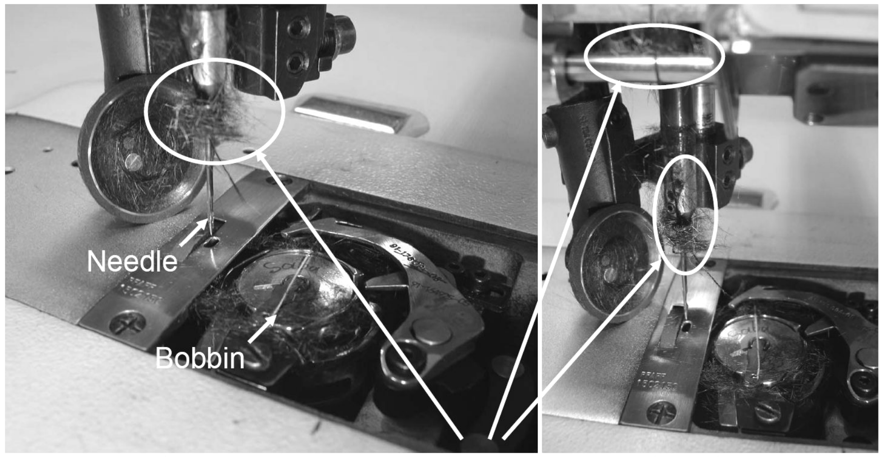


Figure 3.11: Pure twisted carbon fiber sewing thread at sewing machine elements

Table 3.1: Threads for preform and assembly sewing

Yarn type		Linear density (Tex = g/ km)	Description	Mechanical properties		Suitable yarns for preform sewing
				Minimum strength (cN)	Elongation (%)	
Spun yarn	Homog-eneous	21 - 120	Made from short or long fibers with twist level around 400 turns/m	~ 550	18 - 25	As needle and bobbin thread
	Blended					
Twisted multi filaments		16 - 400	10-50 filaments, twisted ~150 turns/ m (each filament 1-4 Tex), (filament diameter: PET- 13-30 µm, Nylon- 17-38)	~ 750	23 - 30	As needle and bobbin thread
Monofilament		3 - 20	Single untwisted filament, thicker and stiffer than normal filament (100-500 µm in diameter)	~ 550	15 - 25	As bobbin thread
Textured yarn		5 - 105	Bulky and with inherent high elongation, tangled/ looped filament orientation	~ 500	27 - 35	As needle and bobbin thread
Core-sheath yarn		18 - 135	High performance filament core, staple fiber sheath	~ 550	15 - 25	As needle and bobbin thread

3.3 Selection factors for sewing thread

Sewing thread must be chosen according to the lay-up characteristics and end-use of the material. The choice of sewing threads according to lay-up structure can be classified according to Table 3.2.

Table 3.2: Choice of sewing thread

Lay-up structures	Sewing thread
Delicate structures like satin or knitted fabrics	Low to zero shrinkage, very flexible and elastic
Multi-directional fabric layers	Sewing thread must be resistant to high temperature, thicker in diameter
Lay-up for very thin laminates	The threads' extensibility must be higher than the fabric extensibility, very flexible (e.g., textured threads)

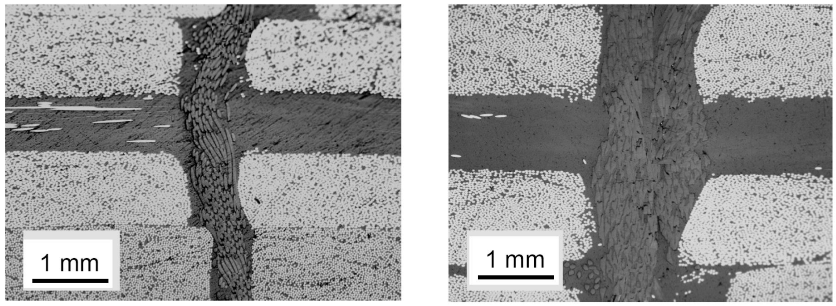
Based on this table, following factors should be considered for the selection of sewing thread to achieve good sewing performance and excellent laminate quality and properties.

3.3.1 According to stitch type

According to the application the seams and the stitch types can be selected. The threads required for the sewing can be selected as per the applications and its suitability for the particular stitch. Table 3.3 shows the threads suitable and applicable for different stitch types. In all the types of stitches, the modified lock stitch is the widely used types and almost all types of sewing threads can be used for this type of stitch formation.

3.3.2 Linear density

The ticket number system, related to Nm (length in meter per gram of mass) and tex (weight in grams per 1000 m length), is now generally used by all the thread manufacturers and industrial thread consumers to describe approximately the finished product. The ticket numbers of synthetic threads are based on the metric count system Nm; approximately three times the metric count of the thread. The thread must occupy no more than 60 % of the width of the eye so that there is no risk of fraying of thread during sewing and the thread flows smoothly during operation. Figure 3.12 shows influence of thread tex on the intensity of division of reinforcing fibers at the localized section. Higher thread linear density adversely affect on the laminate performance [3].



Thin thread inside the laminate (13 tex) Thick thread inside the laminate (27 tex)

Figure 3.12: Influence on thread thickness on the laminate

Selecting with the appropriate size of thread for a particular application is very important to check the thread performance during sewing and afterwards in the seam. However, the choice is not always easy which is depends on the many factors that includes but not restricted to seam strength, fabric weight and type, end use, stitch type, seam type, needle size, direction of sewing, etc.

Table 3.3: Applicability of threads

Stitch type	**Seam type**	**Thread applicable**
Modified lock stitch	Fixing and positioning	Thin, flexible, high elongation polyester
	Assembling	Thicker polyester, Nomex® or Kevlar®
	Structural (3-D)	Carbon, glass, Kevlar®
Chain stitch	Fixing and positioning	Medium thick, less elongation polyester
	Assembling	Thick, less elongation polyester, Kevlar®
One-sided stitch	Assembling	Thick polyester
	Structural (3-D)	Carbon, glass, Kevlar®
Blind	Fixing and positioning	Medium thick polyester
	Assembling	Polyester, Nomex® or Kevlar®
Tufting	Assembling	Polyester, Kevlar®, glass
	Structural(3-D)	Carbon, glass, Kevlar®

The amount of sewing thread influences the amount of reinforcing fiber volume content in the preform. Figure 3.13 shows thread content in the sewn preform with stitch density 3.33 stitches/cm^2. Figure illustrates that, as the thread linear density increases, thread content in the preform also increases and absolute reinforcing fiber content reduces to certain extent (if the sewing thread material is not the same as reinforcing material).

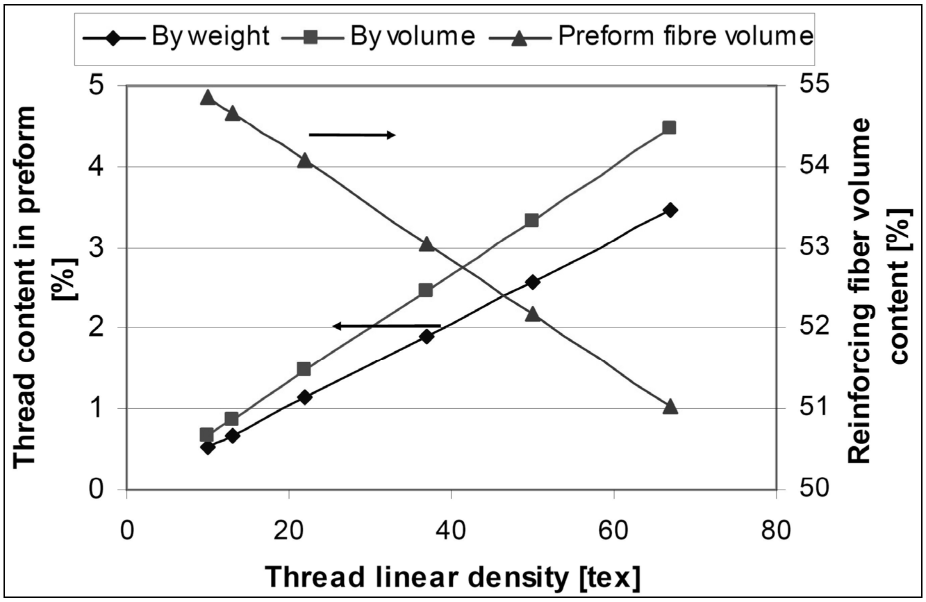


Figure 3.13: Influence on thread thickness on fiber content in compete preform

3.3.3 Selecting the thread packages

The introduction of high-speed industrial sewing machines has tended to increase the use of number of different types of supply packages. The choice of thread package depends on the type of sewing operation. In fixing and positioning sewing, the medium size packages (5000 m) are used; in this case, a frequent change of thread is not necessary. The common most type of packages being used is a tapered cone. Unwinding of the package is depends on the type and amount of twist, which avoids both the loss of twist and snarling (torque) effect. In case, if the package size is too large, the thread guiding path and machine parameters needs to be changed.

For bobbin threads, some manufacturers produce additional small packages such as ready-wound flanged shuttle bobbins for lockstitch machines. But in case of bobbin threads, users do not have much flexibility in terms of thread package. Rather, for a fault-free stitch formation, a fix sized package is a must. Considering the above criteria, sewing thread for particular application can efficiently be selected and implemented for the preform manufacturing.

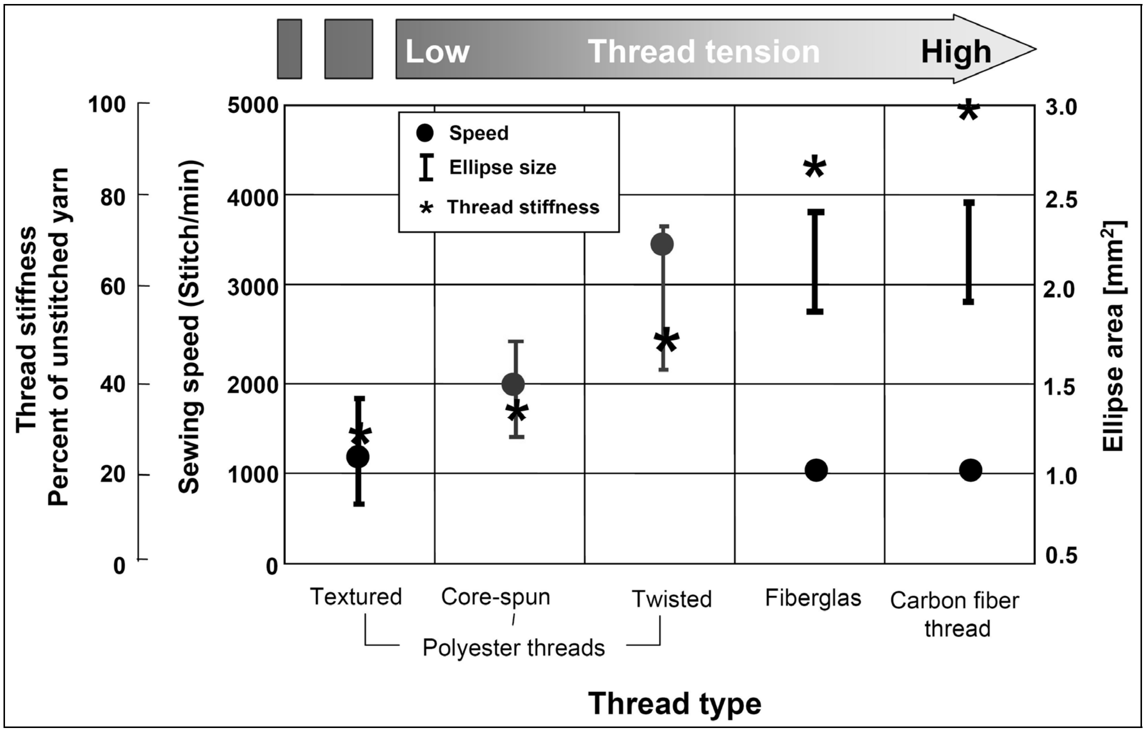


Figure 3.14: Commonly used threads in preform manufacturing [91]

A summary of commonly used threads based on the sewing speed, stiffness, required thread tension, and caused stitch-holes is presented in the Figure 3.14. Textured polyester threads can work only at lower thread tension and only up to 1300 SPM to get required stitch geometry. Whereas, twisted multifilament threads can withstand higher thread tension and maximum sewing speed can go up to 3500 SPM. Delicate but high performance threads made up of carbon fibers needs very high thread tension but it should run at low sewing velocity to reduce the chances of frequent thread breakages.

4 Quality evaluation of sewn preforms and composite laminates

Incorporation of sewing thread in the third dimension of reinforcing material is a base of transverse sewing. The associated parameters of sewing process and caused effects are the criteria for evaluating preform quality and later the FRPC quality. The content of this chapter is focused on the analysis of micrographs of stitched (modified lock stitch) preforms as well as laminates to investigate the disturbance caused at in-plane fiber orientation and the geometrical extension of the ellipse formation by sewing process. Laminate surface imperfection due to matrix shrinkage at ellipse, change in fiber volume at localized sections, and imperfections inside the laminate is investigated. Furthermore, approaches to improve preform and laminate quality is also discussed.

4.1 Formation of ellipse

The sewing process causes spreading of the reinforcing fibers during the needle penetration, which forms a fiber-free contour over the surface and inside the preform structure. The contour size is based on the position of sewing thread is assumed as an ellipse shape for calculation purpose. The fabric lay-up structure, thread variables, and machine parameters define the area of this ellipse. Figure 4.1 shows theoretical and actual ellipse geometries.

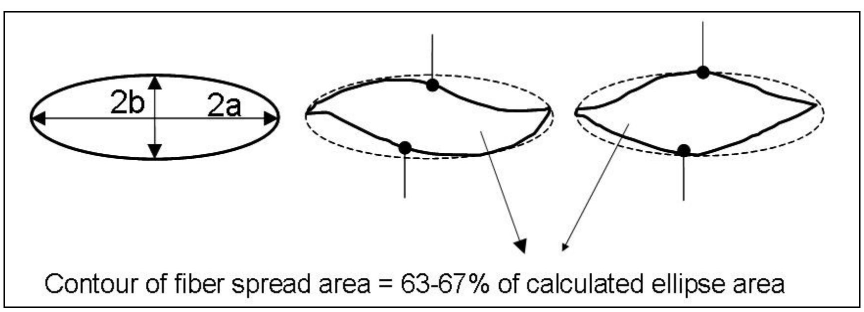


Figure 4.1: Ellipse geometries considered for calculations

The first theoretical ellipse values can be calculated by measuring minor and major axis of fiber-spread region and then multiplying factor of fiber-spread (0.65) a near real ellipse area can be calculated. The fiber-spread factor was investigates by examining approx. 400 fiber-spread regions from various preforms and composite laminates.

Figure 4.2 shows micrographs of sewn woven fabric preform and a composite laminate at stitched section (top view). Polyester thread position at the scanned image of preform and the laminate is also visible in figure. Micrograph of laminate clearly shows typical minor axis (2b) and major axis of ellipse (2a).

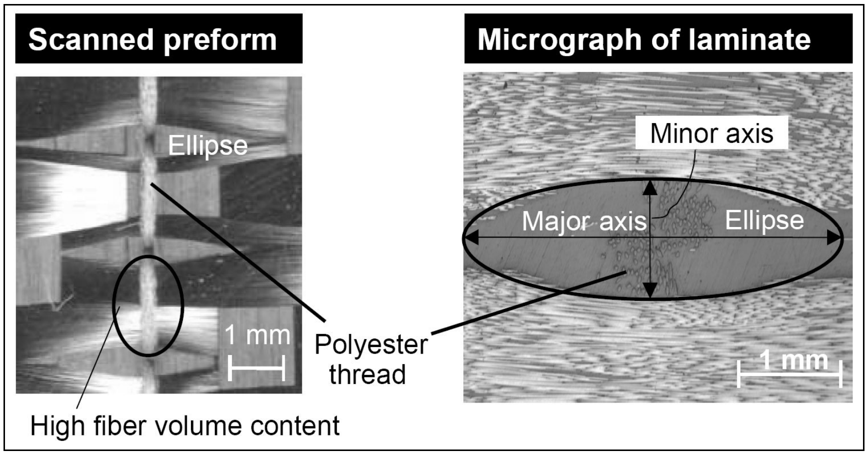


Figure 4.2: Major and minor axis of ellipse

Formation of ellipse in the laminate is totally depends on fabric geometry, sewing thread geometry, thread tension, and laminate thickness. Influence of various factors is explained in detail in following sections.

4.1.1 Influence of textile material lay-up

For the manufacturing of composite laminates, textile material needs to be positioned in a specific orientation. The ellipse formation and fiber disorder in each layer are observed in the direction of the reinforcing fibers which is again independent of stitch direction [92]. Figure 4.3 shows schematic diagram of [-45/0/+45/90] lay-up with penetrated sewing thread and formed ellipses in the in-plane and through-the-thickness direction. Through-the-thickness cross-section indicates the separation of reinforcing fibers very clearly. The minimum fiber distortion can be observed in fiber lay-up which is oriented in parallel to sewing direction.

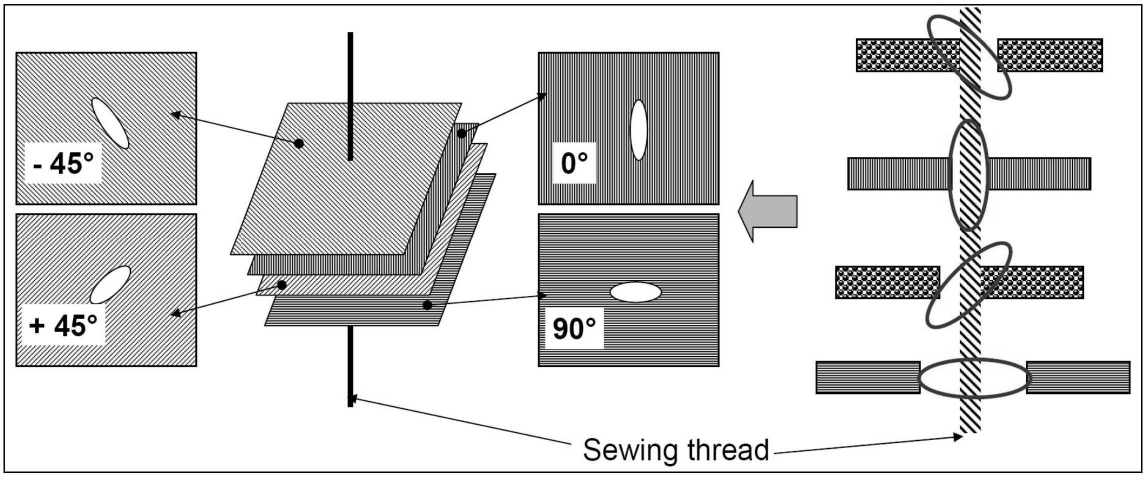


Figure 4.3: Influence of lay-up on the ellipse formation

4.1.2 Influence of stitch type

During the sewing operation, though the needle and bobbin thread tensions are adjusted for modified lock stitch, due to the irregularities in sewing thread, irregular friction between fabric and thread, and excessive machine speed, the absolute needle thread tension may fluctuate. This phenomenon of varied thread tension may leads to formation of standard lock stitch geometry. It means needle thread pulls the bobbin thread from $1/10^{th}$ to 1/2 of the laminate depending on the overall laminate thickness. In lock stitch, due to the knot inside the laminate, intensity of ellipse formation and ellipse dimension at the particular layer may also alter. Thus, apart from fiber discontinuity at upper layer, the bottom layer of the laminate may also creates discontinuity in the reinforcement structure.

Generally, in the ideal modified lock stitch, top surface of the laminate (needle penetration surface) is highly affected in terms of fiber distortion, whereas, theoretically, bottom surface does not show any sign of fiber distortion. But, in lock stitch or actual modified lock stitch, pulled-in bobbin thread destructs bottom layers of the laminate. Figure 4.4 a shows ellipse sizes at various layers (1 to 8 layers on x-axis means top to bottom) with respect to type of stitch geometry (Figure 4.4 b).

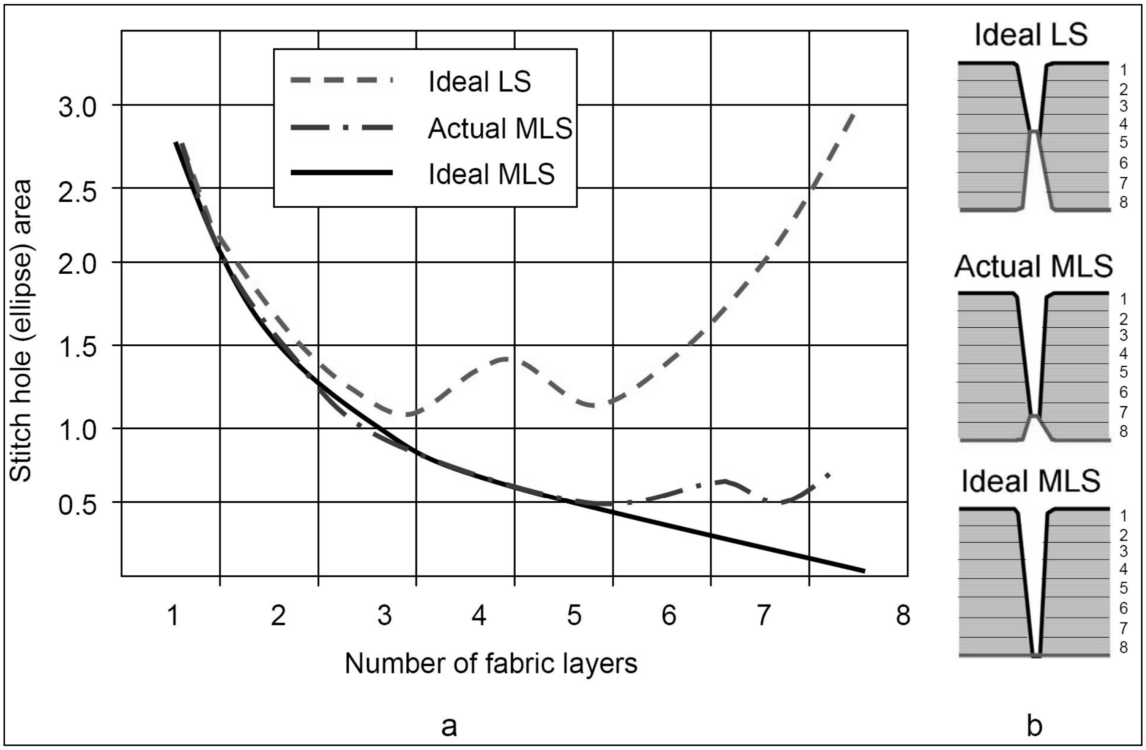


Figure 4.4: a) lay-up and stitch type dependent ellipse formation and b) stitch type (LS: lock stitch, MLS: modified lock stitch)

4.1.3 Influence of thread packing

As stated earlier, thread geometry affects the stitch performance and it has been observed that the ellipse areas formed by different threads have different dimensions. Again, due to applied forces on the sewn preform, during the LCM processing the thread packing can change, which causes change in the ellipse shape and dimensions. Figure 4.5 shows influence of thread packing on the ellipse minor axis and consequently the major axis. Densely packed thread leaves small ellipse behind whereas randomly oriented thread causes higher fiber-spread.

The factor which affects thread packing is thread geometry, which includes, twist, bulk, number of filaments in the cross-section, etc. Neither soft twisted (soft packed) nor hard twisted threads are recommended for the development of stitched preforms.

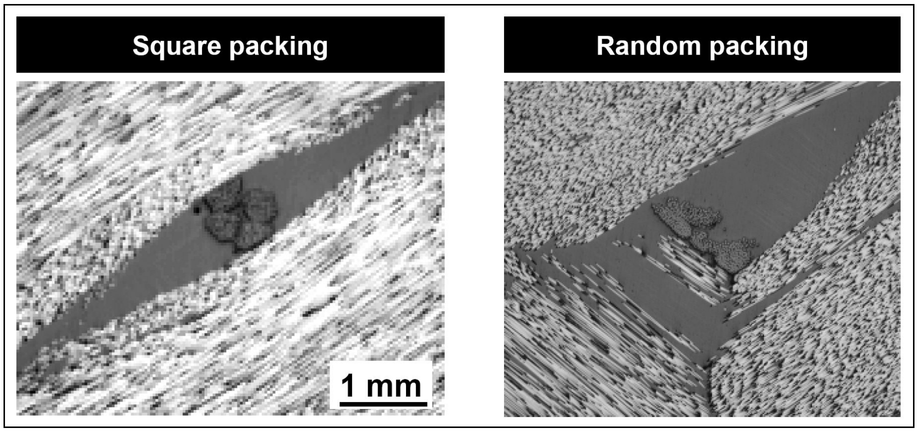


Figure 4.5: Influence sewing thread geometry

4.1.4 Statistical analysis of influencing factors

Influence of thread tension (low and high), fabric type (woven and NCF), thread type (twisted and textured), and stitch pattern (low stitch density and high stitch density) on the intensity of ellipse formation have been statistically analyzed. Analysis of variance (ANOVA) method was used for evaluating significance of each parameter. Figure 4.6 shows factorial design table and ANOVA table.

Yate's algorithm method was used for analyzing the data and at the end; the factor sum of squares can be obtained from the 2^n factorial design table which will be the important input for ANOVA. The experiments were not replicated, thus, there is no unbiased estimate of the experimental error. Nevertheless, the assumptions have been made that the three and four factor interactions are of no practical significance, and therefore they are combined in such a manner (Figure 4.6 b) that it provides the residual or error mean square. All the other mean squares are divided by this to provide "F" values. The results have been implemented to test the significance of the main influencing variables and interactions of two variables, by comparing them with the corresponding entries in the "F test" table [93].

From the ANOVA table (Figure 4.6b) it can be concluded that the type of fabric (woven or NCF) influence at 2.5 % level of significance, because F value for factor A (fabric type) = 10.65, which is just beyond the $F_{1,5,0.025}$ value (10.0). Thread tension and thread type influence the ellipse formation in laminates at 1 % level of significance. In the table is can be clearly seen that the F values for B and D factors (thread tension and thread type) are 21.739 and 78.478 respectively and that are much beyond the $F_{1,5,0.1}$ (16.3). F table for 2^n factorial design is illustrated in appendix. Variation in stitch pattern or stitch density does not have any influence on the ellipse size. Interaction of the thread tension and fabric type (BC interaction) is approaching 5 % level of significance (F value for BC interaction, 1.95 is approaching $F_{1,5,0.05}$, i.e., 6.6).

n = 4

A	Fabric
B	Thread tension
C	Stitch pattern
D	Thread type

For calculation					
		Woven		NCF	
		Tension1	Tension 2	Tension1	Tension 2
Pattern 1	Thread 1	2	2.1	1.8	1.9
	Thread 2	1.4	1.6	1.2	1.5
Pattern 2	Thread 1	1.8	2.1	1.5	2
	Thread 2	1.5	1.5	1.1	1.6

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\+

Yate´s Algorithm

Row number	1	2	3	4	x	1	2	3	4	Factor effect	Factor sum of squares	Factor
1	-	-	-	-	2	3.8	7.8	15.2	26.6	1.66	-	mean
2	+	-	-	-	1.8	4	7.4	11.4	-1.4	-0.18	0.12	A
3	-	+	-	-	2.1	3.3	5.7	-0.8	2	0.25	0.25	B
4	+	+	-	-	1.9	4.1	5.7	-0.6	0.8	0.10	0.04	AB
5	-	-	+	-	1.8	2.6	-0.4	1	-0.4	-0.05	0.01	C
6	+	-	+	-	1.5	3.1	-0.4	1	2.22E-16	0.00	0.00	AC
7	-	+	+	-	2.1	2.6	-0.3	0.2	0.6	0.07	0.02	BC
8	+	+	+	-	2	3.1	-0.3	0.6	0.6	0.08	0.02	ABC
9	-	-	-	+	1.4	-0.2	0.2	-0.4	-3.8	-0.48	0.90	D
10	+	-	-	+	1.2	-0.2	0.8	8.9E-16	0.2	0.03	0.00	AD
11	-	+	-	+	1.6	-0.3	0.5	0	4.44E-16	0.00	0.00	BD
12	+	+	-	+	1.5	-0.1	0.5	2.2E-16	0.4	0.05	0.01	ABD
13	-	-	+	+	1.5	-0.2	-2.2E-16	0.6	0.4	0.05	0.01	CD
14	+	-	+	+	1.1	-0.1	0.2	-4.4E-16	2.22E-16	0.00	0.00	ACD
15	-	+	+	+	1.5	-0.4	0.1	0.2	-0.6	-0.08	0.02	BCD
16	+	+	+	+	1.6	0.1	0.5	0.4	0.2	0.03	0.00	ABCD

a

Factor	sum of squares	degrees of freedom	mean squares	F
A	0.12	1	0.12	10.652
B	0.25	1	0.25	21.739
C	0.01	1	0.01	0.870
D	0.90	1	0.9025	78.478
AB	0.04	1	0.04	3.478
AC	0.00	1	3.08E-33	0.000
AD	0.00	1	0.0025	0.217
BC	0.02	1	0.0225	1.957
BD	0.00	1	1.23E-32	0.000
CD	0.01	1	0.01	0.870
ABC	0.02			
ABD	0.01			
ACD	0.00			
BCD	0.02			
ABCD	0.00	5	0.0115	

F : see table A5

k1 =	1	1	1
k2 =	5	5	5
alpha =	0.05	0.025	0.01
	5%	2.50%	1%
$F_{k1,k2,alpha}$	6.6	10.0	16.3

b

Figure 4.6: a) 2^n factorial design based on Yate's logarithm and b) ANOVA table for ellipse formation

Selection of fabric type for particular composite application can not be altered according to this analysis. Furthermore, stitch density can be varied only according to required preform compaction and fiber fixation. Thus, for various reinforcing textile fabrics, selection of proper thread tension to keep the fiber distortion at the lower level is a must.

4.2 Laminate imperfections

4.2.1 Surface quality due to matrix shrinkage

As discussed in the above sections, fiber-spread may occur during the sewing of preforms and this leads to formation of fiber free zones. After the resin injection, there are chances of resin accumulation at these zones. Depending on the type of resin system used, shrinkage of this accumulated resin can occur. This phenomenon may cause uneven laminate surface or micro-cracking. Furthermore this region may cause stress concentration under the mechanical load. Figure 4.7 shows the results of surface analysis at the stitch section. In this example, 31.1 μm resin shrinkage depth has been observed. However, these types of shortcoming can be avoided by reducing the ellipse formation which has been explained in section 4.1.

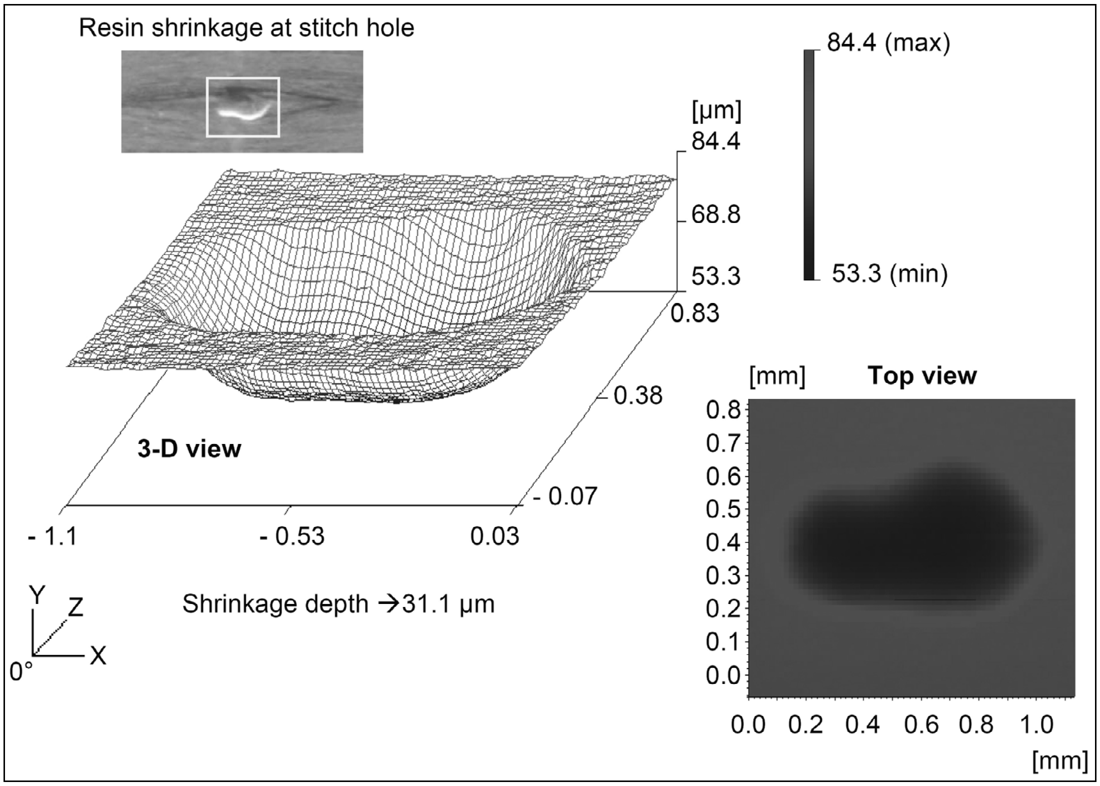

Figure 4.7: Resin shrinkage at stitch-hole zone and 3-D surface evaluation

4.2.2 Influence on localized fiber volume content

At the localized section, fiber volume fraction level varies from zero to maximum due to the ellipse formation. The maximum volume fraction can be reached up to 70 %. This effect is totally depends on the thread specifications and machine parameters. Difference in the fiber volume content may affect the micro structural and mechanical properties. Figure 4.8 shows sewn preform and laminate with different fiber volume content. Due to the accumulation of fibers under the sewing thread, a relatively thicker section may form. This may create difficulties in mold closure during the close mold RTM process and uneven laminate surface in the vacuum assisted RTM processed laminates. Apart from this, due to high localized fiber volume, fiber impregnation in this zone is quite difficult.

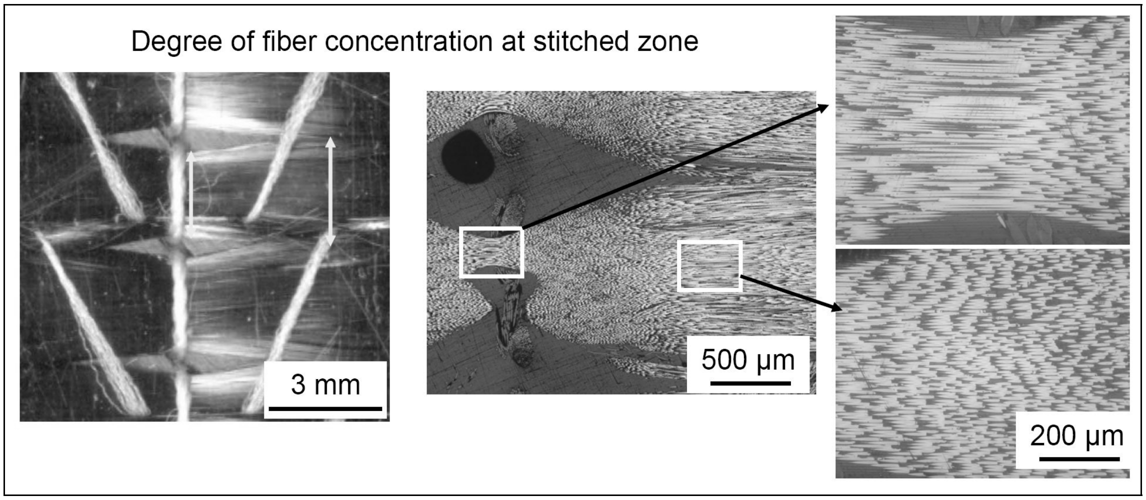

Figure 4.8: Localized fiber volume content at stitched zone (preform and laminate)

4.2.3 Through-the-thickness imperfections

At the stitched section, voids and unimpregnated sewing thread are the commonly faced challenges. The cause of void formation is generally the degassing of applied chemicals and its incompatibility to the matrix system. By applying a proper thread finish, reduction in voids and proper thread impregnation can be accomplished.

Due to the penetration of sewing needle twice at the same location (depends on the type of sewing pattern), widening of stitch-hole may be possible. This may causes through-the-thickness resin rich area at the particular section. Figure 4.9a) shows single and double penetration of needle and formed stitch. This cause enlarged resin rich area (due to excess thread content at the localized zone) and further voids formation or unimpregnated thread. Figure 4.9b) shows through-the-thickness micrograph of the laminate with voids.

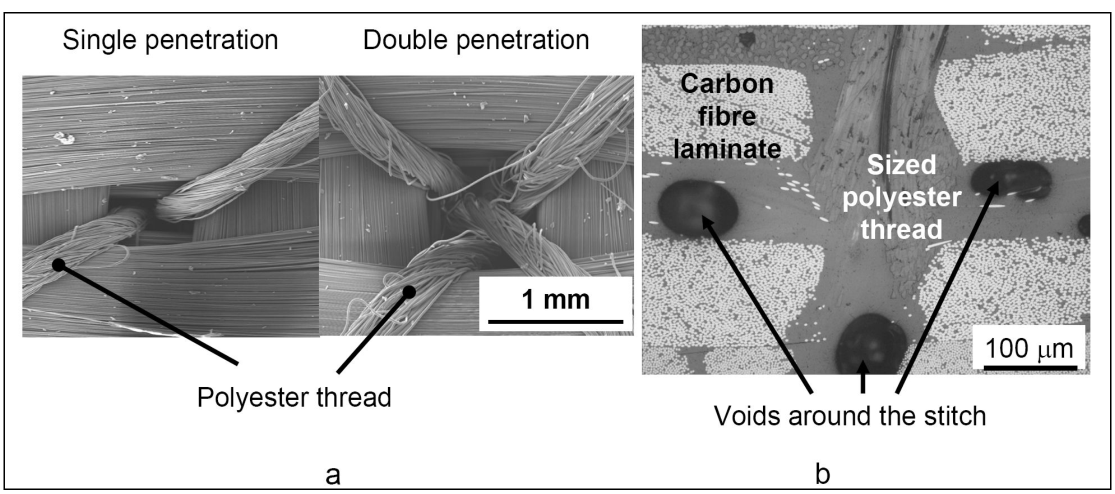

Figure 4.9: Laminate micrographs (a) stitch positions, single and double penetration and (b) through-the-thickness section at stitch (voids)

Another common error observed during the sewing process is the missing stitches. Small stitch length and high speed causes poor interloopment of a thread at bobbin gripper. As an effect, needle penetrates through the reinforcing fabric and comes out without stitch formation. Figure 4.10a shows micrograph of the missing stitch location. Here the programmed stitch length was 2.5 mm but due to missing stitch the actual stitch length was measured to be 5 mm. Subsequently split in the fiber bundle is a common effect of such phenomenon.

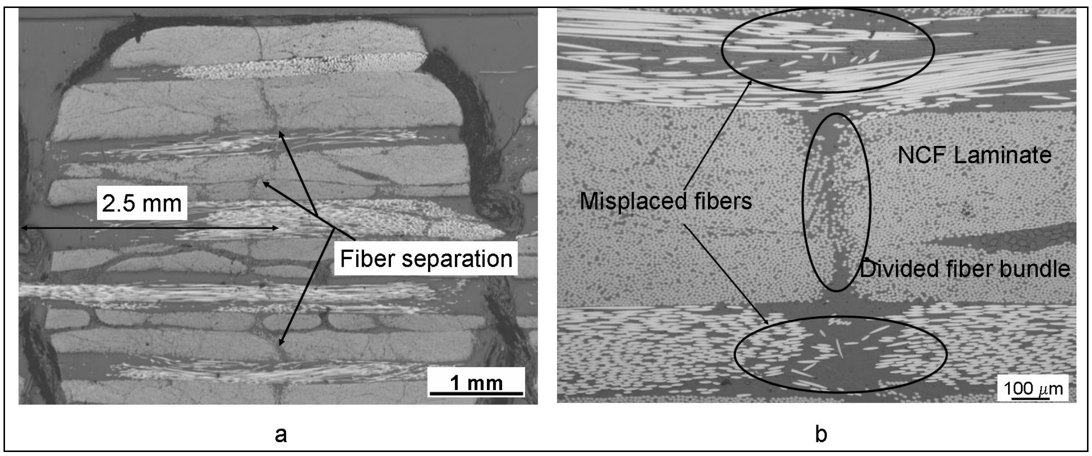

Figure 4.10: a) reinforcing fiber separation due to missing stitch, b) fiber misplacement due to false stitch

Sewing action disturbs the orientation of reinforcing fibers, this may results inter and intra-layer fiber misalignment. Figure 4.10b shows NCF laminate with misplaced and disoriented fibers which may lead to poor mechanical performance of the laminate. Proper combination of stitch length, material thickness, and adjustment of machine speed can help to reduce the fiber distortion significantly.

Applied spin-finish or sizing on the sewing thread is a major role playing factor in void formation and poor impregnation of thread. The silicon oil based sizing used for the standard polyester thread contains up to 4 % of oligomers. This hinders impregnation of polyester thread and on application of heat, during curing cycle, degassing of this substance may results the void formation. The phenomenon of void formation not only restricted to the laminate surface but it extends around the stitch, inside the laminate. Figure 4.11 shows gas bubbles formed over the laminate surface. The voids inside the laminate around the sewing thread are shown in Figure 3.2.

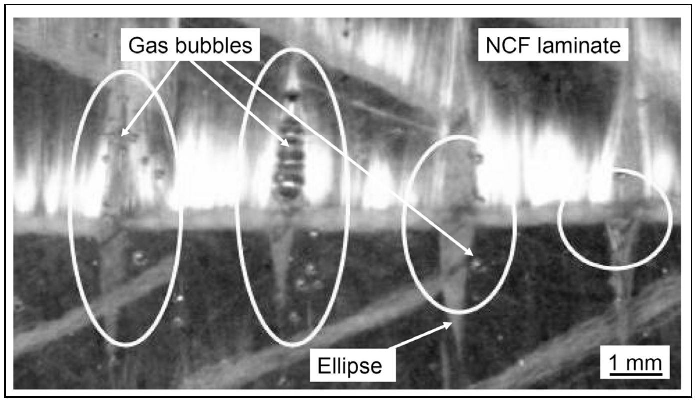

Figure 4.11: Degassing of chemicals and gas bubble formation

4.3 Approaches to reduce imperfections

Imperfections like ellipse formation and related side effects such as void formation, poor fiber impregnation, resin richness, etc. can be reduced to certain extent by using various methods. This includes chemical treatment of thread, adjustments of sewing machine parameters, selection of sewing thread, etc.

4.3.1 Modified sewing threads to reduce ellipse size

Use of definite sewing thread for specific delicate reinforcing fiber structure is obligatory and it has been explained in previous chapter. Judicious utilization of specialty and commodity textile threads can help to reduce sewing imperfections in the subsequent operations.

Textured polyester threads

The compaction of preforms is subject to applied pressure during the RTM processing. During this compression, preform thickness tends to reduce and rearrangement of reinforcing fiber takes place. Apart from this, stitch geometry may change according to the used thread and machine parameters and change in ellipse size can happen.

Since textured threads have soft and looped structure, the stitch-hole closing during preform compaction is much more significant than the multifilament thread. Figure 4.12 shows intensity of reduction in ellipse size in twisted multifilament thread and textured thread after the application of compaction pressure on the preforms (compaction pressure applied to achieve approximately 65 % fiber volume content).

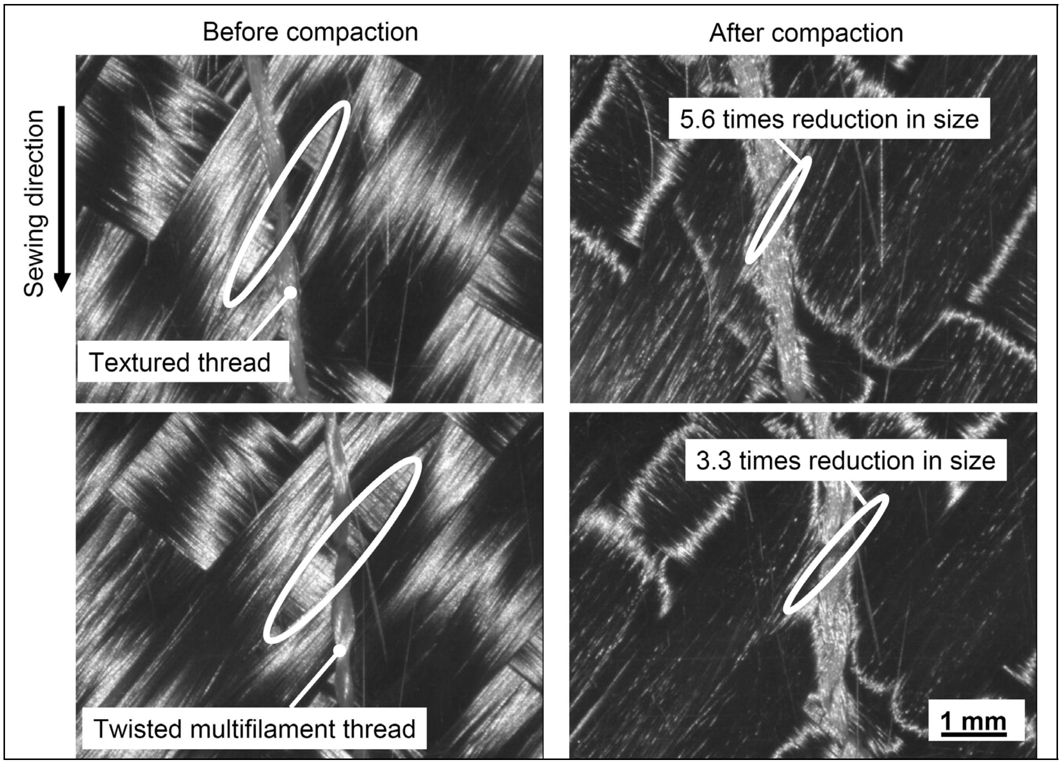

Figure 4.12: Influence of preform compaction on stitch-hole closing with respect to chosen thread type

Epoxy soluble threads

In section 3.2 of Chapter 3, soluble threads and phenomenon of dissolution has been explained. Soluble thread dissolves in the specific epoxy matrix at a particular temperature. Here, in Figure 4.13 an example of liquid crystalline polymer (LCP) is taken into consideration which dissolves in RTM grade single component epoxy matrix system. The dissolution phenomenon takes place at a very particular curing cycle. This causes local movement of reinforcing fibers and forces acting on the thread (thread tension during sewing) can be released off. Furthermore, flow of liquid matrix makes fiber dissolution phenomenon easier which also helps to reduce the ellipse size and magnitude of stitch-holes.

Figure 4.13 shows change in ellipse size at various temperatures. At 100 °C the filaments those are swimming in the epoxy matrix starts softening and thus, acting force on the reinforcing fiber be reduced continuously. As the temperature increases, the filaments dissolve completely in the matrix (at 125 °C) and in the later stage disperse along the laminate. At the same time, distorted reinforcing fibers tries to reorient, however, in absence of any positive control over this phenomenon, only partial closing of ellipse is possible.

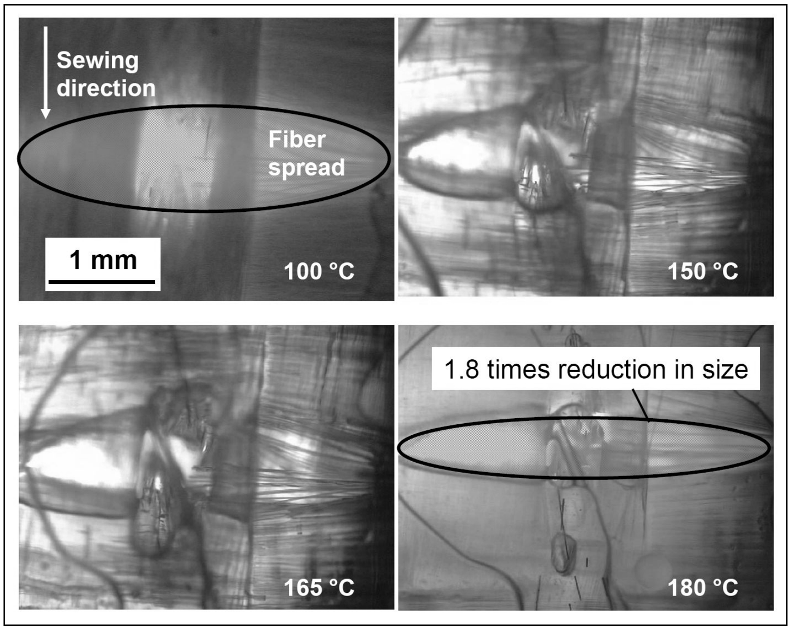

Figure 4.13: Change in ellipse size as a function of sewing thread dissolution

Low melting point threads

Utilization of fibers with the low melting point is also based on the principle which is similar to the dissolving fibers. This type of fibers helps to reduce elliptical fiber-spread in the FRPC laminates. Quick melting sewing thread melts during the hot resin injection or hot curing and makes reinforcing fibers free from binding force. After this, the reinforcing fibers are free to move within the allowed empty space. Sometimes, the free movement of fibers can be restricted by the molten thread polymers, which forms a small polymer ball on the either side of laminate or at the laminate centre.

4.3.2 Selection of thread tension to reduce ellipse dimensions

Low to medium thread tension during the sewing process exerts less force on the preform resulting lower distortion of fibers. This causes lower ellipse size compared to high thread tension [66]. During the resin impregnation, reinforcing fibers around the seam can reorient easily and thus, helps to reduce stitch-holes. Due to lower thread tension up to 50 % reduction in ellipse size is possible. But if high thread tension is applied this possibility reduces to only 20 %, because, higher thread tension causes not only in-plane but also out-of-plane irreversible distortion.

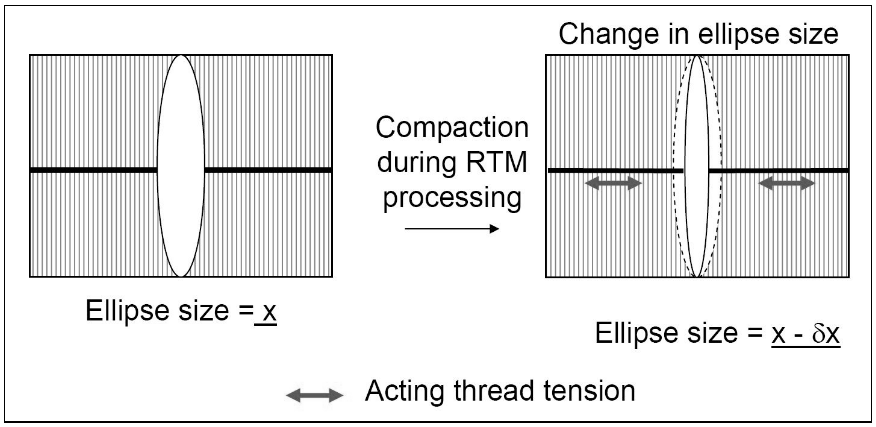

Figure 4.14: Thread tension as a function of change in the ellipse size

4.3.3 Thread washing and resizing

For proper impregnation of polyester thread and manufacturing of void free laminates, the applied thread sizing must be removed and additional, process compatible sizing has to be applied. By using chemical treatments, oligomeric substances can be washed out (99 % removal) from the thread [81] and additional sizing can be applied on the thread which makes it again sewable. Additional sizing is a prerequisite for better sewing effect; otherwise, thread could be rough, poor antistatic, and abrasive. 3 % of thermally stable sizing can be the best suitable for sewing and in terms of better laminate quality (no voids and completely impregnated polyester thread.

4.4 Summary

Preform quality in terms of fiber-spread, ellipse formation, missing stitch, etc. and defects formed due to these imperfections are explained in this chapter. Spreading of fibers due to sewing thread tension and other parameters can results various flaws in the composite laminate, for instance, varied fiber volume at localized sections and resin shrinkage at stitch-hole region. Degassing of sewing thread sizing causes voids inside the laminate and on the surface.

Sewing threads with improved geometrical characteristics, special threads made up of epoxy soluble or quick melting polymer, RTM tooling process, and liquid matrix injection process can help to reduce ellipse size and improve laminate quality. Apart from this, process compatible sewing thread sizing can reduce degassing, bubble formation, and void formation phenomenon. Further preform characterization in terms of preform compaction is explained in the next chapter.

5 Examination of preform compaction

Preform engineering aspects and tailored reinforcements are solely related to the LCM processes [26]. In order to reduce the process time to manufacture FRPC laminates, it is essential to reduce tool loading time. For this reason, the utility costs, forces acting during the LCM process, stitch pattern, and stitch formation have to be taken into consideration. Sewn preform geometries have unique compression properties and therefore behaves in a different manner in terms of processing and mechanical performance. To understand this relationship, it is essential to relate the sewing parameters with the LCM processing parameters.

The current work is focused on the experimental analysis of preforms with four different parameters: sewing thread, sewing thread tension, stitch density, and textile fabrics. Basic phenomenon of preform compaction is explained at the beginning. Influence of selected variables on the compaction behavior of sewn preforms is investigated. Furthermore, regions of porous and fibrous compaction and corresponding linear and non linear zones in the compression curve are explained in detail.

5.1 Phenomenon of preform compaction

The phenomenon of preform structural compaction is depends on the parameters of a particular panel, e.g., fabric material used, fabric geometry, tailored reinforcements, etc. Multi-directional deformation of a preform panel is an outcome of acting in-plane compaction pressure. The preform compaction primarily represents the porous media compaction and secondarily the fibrous compaction [94].

In woven fabric preforms, majority of compaction corresponds to the change in panel thickness which is dominated by porous compaction. Apart from this, due to rearrangement of fibers during the fibrous compaction, woven structure also deforms in linear direction. In sewn preforms, the number of individual stitches forms localized boundaries, which restricts the linear movement of roving in the woven fabric, which helps to avoid the linear deformation of fabric lay-up.

Compaction behavior of sewn preform is influenced by different sewing parameters [95]. Many researchers studied the compaction of woven fabric preforms [94-97]. These studies were based on the analysis of 3-D micromechanical model and pressure thickness relationship. Grimsley et al. explained the compaction behavior of stitched multi-axial noncrimp fabric material in dry and wet condition during the vacuum assisted resin transfer molding (VARTM) [98]. The time dependent tooling forces acting on the unstitched preforms during RTM process are also of great importance [99]. Some of these parameters studied can be related to the shortcomings of the stitched preforms.

In this chapter, the influence of sewing thread tension and stitch pattern on the preform compaction behavior is explained. The relationship between applied compaction pressure and corresponding fiber volume fraction has been evaluated. Figure 5.1 shows process flow for the experimentation.

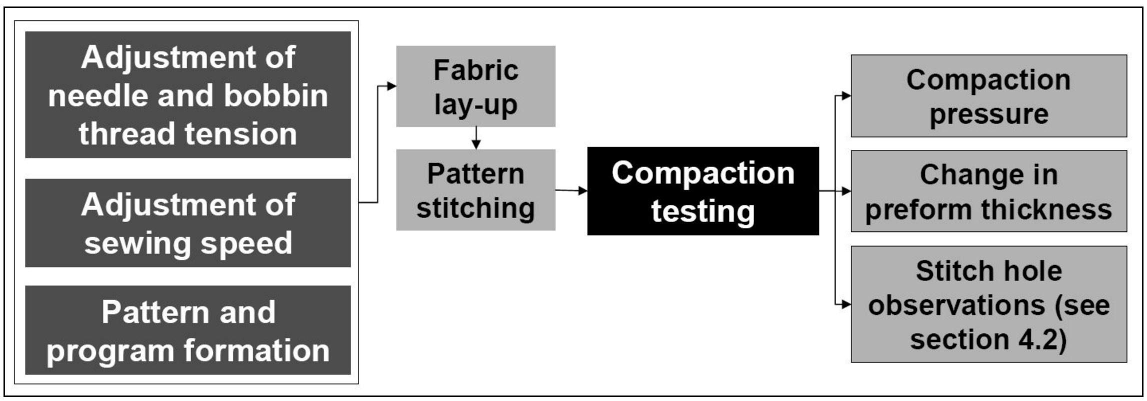

Figure 5.1: Process flow for compaction testing and analysis

5.2 Material and methods

Material selection was based on the frequently used reinforcing material data base. Bi-axial noncrimp fabric (380 grams per square meter, gsm) and woven 2/2 twill fabric (400 gsm) with approximately same area weight were selected for the experimentation. Two different thread types namely textured thread and twisted multifilaments, varied thread tension, and different stitch densities were selected to investigate the effect of individual sewing parameter on the selected reinforcing materials. Figure 5.2 shows the selected parameters.

According to the process flow plan, the preform panels were manufactured. Figure 16 shows three different types of sewing patterns selected for the preform manufacturing. Here, as an example, twill woven fabric stitched with the twisted multifilament at high thread tension with 20 x 20, 10 x 10, and 5 x 5 sewing patterns are presented.

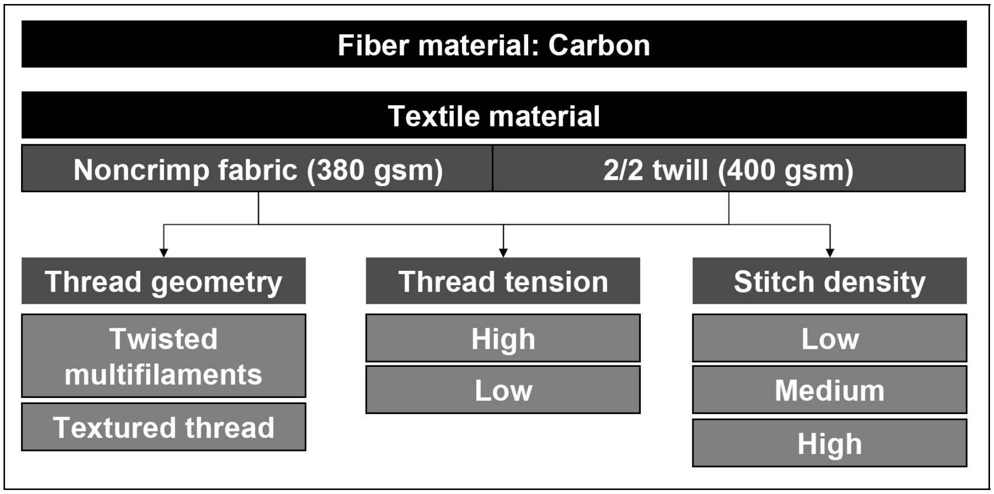

Figure 5.2: Parameters selected for the experimentation

20 x 20 means a square of 20 mm x 20 mm stitch pattern was developed on the preform. A low stitch density (3.33 stitches/cm^2) was achieved by 20 x 20 sewing pattern, similarly, medium stitch density (6.67 stitches/cm^2) was achieved by 10 x 10 sewing pattern and high stitch density (13.33 stitches/cm^2) was achieved by 5 x 5 sewing pattern (Figure 5.3).

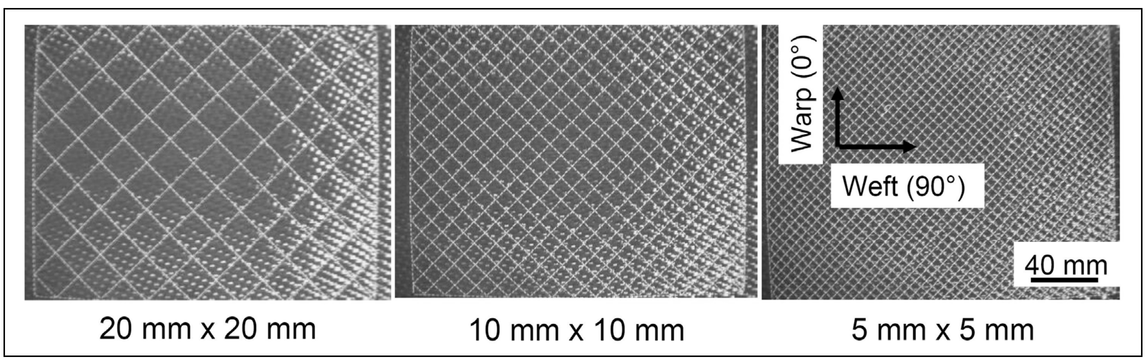

Figure 5.3: Types of sewing patterns

Subsequently, the preforms sewn with varied sewing parameters and all the sewn panels were tested and analyzed for the compaction behavior. A laboratory scale compaction measuring device was used to measure the required compaction pressure and corresponding preform thickness. Figure 5.4 shows testing set-up and details of the testing equipment. Unstitched lay-up of the reinforcing fabric ([0/90] four layers) was also tested with the similar method. LabVIEW software from National Instruments was used for the interface between compaction instrument, camera for the stitch-hole monitoring, and computer. Three measurements per sample were performed and mean of these readings was plotted in a compaction pressure vs. fiber volume content curve. Figure 5.5 shows compaction curves for NCF preform (single sample) measured at three different locations.

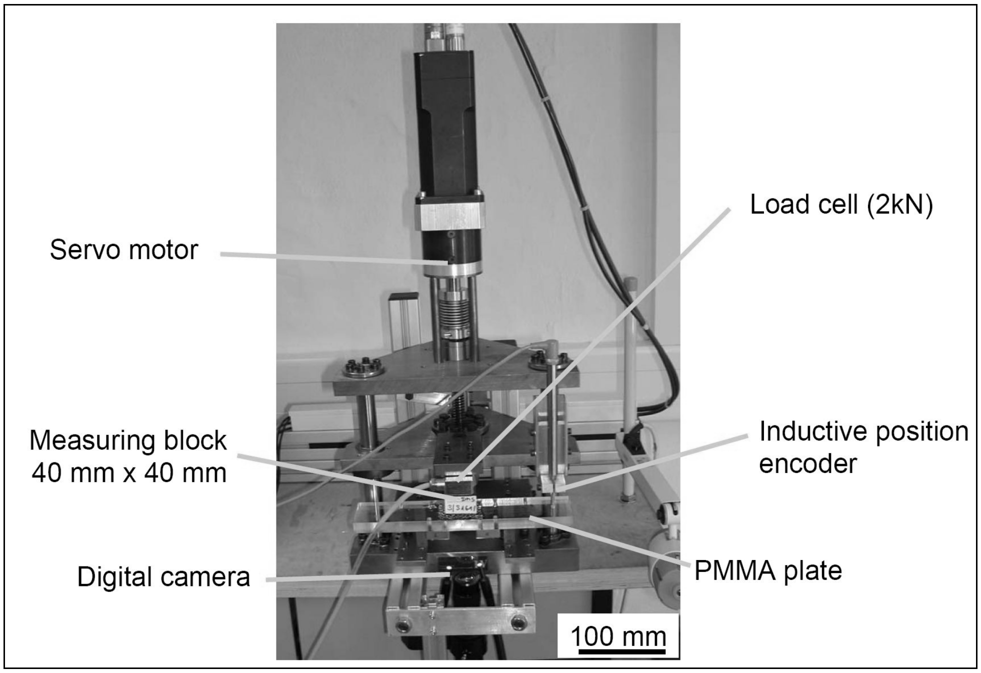

Figure 5.4: Compaction instrument testing set-up with Plexiglas and camera

The graphical data was analyzed in order to evaluate the influence of sewing parameters on the compaction behavior. The data transferred by the camera in terms films and pictures were also stored and analyzed for the influence of sewing parameters on the change in ellipse size at particular compaction pressure (Chapter 4, Figure 4.12).

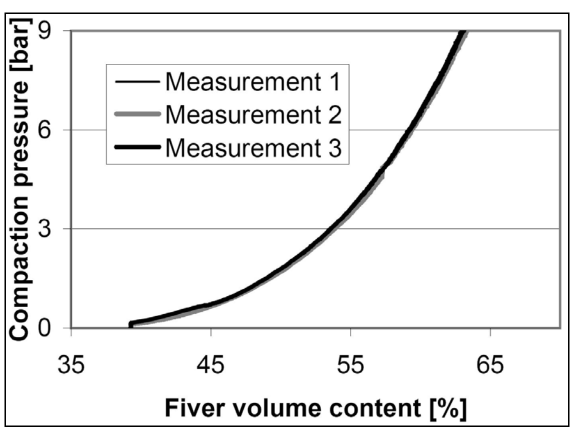

Figure 5.5: Compaction curve readings (three per preform)

5.2.1 Influence of thread tension during sewing

Preform sewn with low stitch density:

Figure 5.6a shows the compression behavior of four layers of [0/90] noncrimp fabric stitched panels in relation with variation in thread tension. Figure 5.6b shows the compression behavior of four layers of [0/90] woven fabric and stitched panels. The effect of compaction pressure on the theoretical fiber volume fraction is explained in both figures. At the start of the test, pressure applied on the preform was dead weight of preform. As the crosshead moves downwards (Figure 5.4), the compaction pressure acting on the preform initiates and subsequent continues reduction in preform thickness was observed. This leads to a continuous increase in the fiber volume till the preform has a certain limit of compressibility.

In NCF preforms stitched with high thread tension (270 cN), roving buckles at the localized stitch zone because of the applied thread tension and warpage and, forms a bulge (warpage and bulge explained in more detail in section 8.1.1). During the preform compaction process, the measuring block rests firstly on the bulged section and then compresses it as the test proceeds. This occurrence needs a very high force for compaction of these types of preforms.

On the contrary, the panels stitched with low thread tension (166 cN) needs a comparatively small amount of pressure to achieve required compaction. Low thread tension in the stitches cause low bulge and allows micro movement of the reinforcing fibers which needs comparatively low force to rearrange the fibrous bundles to required volume.

At the initial stage of compaction, preforms stitched with the high thread tension possesses approx. 43 % fiber volume and preforms stitched with low thread tension posses 40 % fiber volume. However, as explained earlier, the final compaction pressure needed to achieve a specific fiber volume is lesser in the case of preforms stitched with low thread tension than it is required for preforms stitched with higher thread tension. Furthermore, precompaction at the stitching stage improves compaction behavior of the preforms sewn with low thread tension than the unsewn preforms.

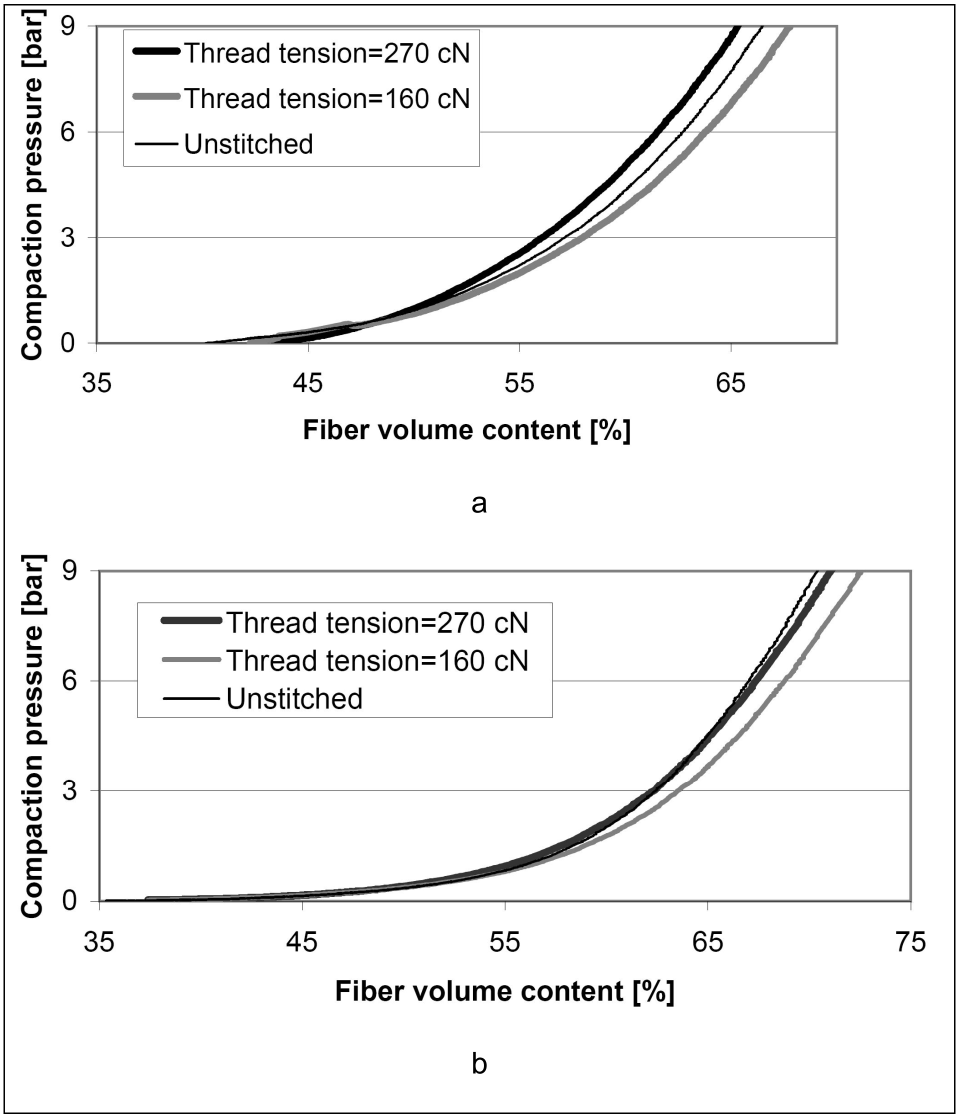

Figure 5.6: Influence of thread tension on preforms (stitch pattern: 20 mm x 20 mm, stitch density: 3.33 stitches/cm^2, thread used: twisted multifilaments) a) NCF $[0/90]_4$ and b) 2/2 twill woven fabric $[0/90]_4$

In case of woven preforms stitched with high thread tension (Figure 5.6b), the preform is compressed partially at the stitching stage itself; nevertheless, there is enough possibility for fiber rearrangement and further compaction. Due to the balance between bulge formation, warpage, and linear deformation, a preform sewn with high thread tension behaves similar to unsewn lay-up.

Preform stitched with low thread tension causes lower bulge and so the lower resistance to compress the preform. Therefore, this preform shows higher fiber volume content at given compaction pressure than the preforms stitched with high thread tension and unstitched lay-up.

Preform sewn with medium stitch density:

As far as NCF preforms are concerned, the results were obtained from the experiments performed with intermediate stitch density (6.67 stitches/cm^2) and low stitch density. Figure 5.7a shows compaction pressure vs. fiber volume content curves for sewn and unsewn preforms. Here, the preforms stitched with high thread tension behaves quite similar to the unstitched lay-up, where as the preforms stitched with lower thread tension requires relatively low compaction pressure.

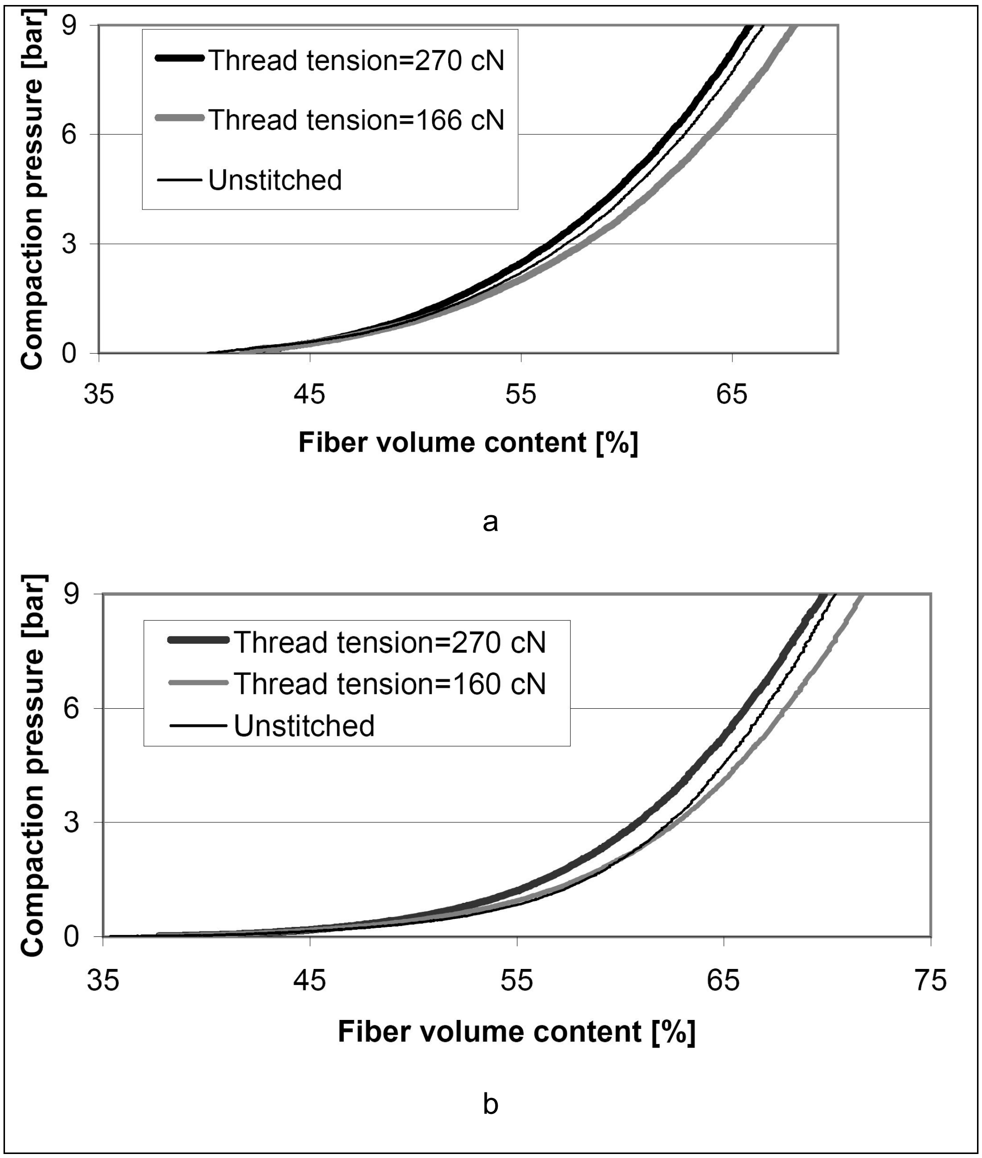

Figure 5.7: Influence of thread tension on sewn preform (stitch pattern: 10 mm x 10 mm, stitch density: 6.67 sttiches/cm^2, thread used: twisted multifilaments) a) NCF $[0/90]_4$ and b) 2/2 twill woven fabric $[0/90]_4$

In case of the woven preforms (Figure 5.7b), due to relatively higher stitch density, intensity of bulge formation is higher. Thus, the preforms stitched with higher thread tension needs higher compaction pressure for particular fiber volume fraction. The preforms stitched with lower thread tension behave similar to an unsewn lay-up till 62 % fiber volume content. Thereafter, preform stitched with low thread tension needs lower compaction pressure than the unstitched lay-up.

Preform sewn with high stitch density:

Unlike above two experiments, the NCF preforms stitched with high thread tension and higher stitch density (13.33 stitches/cm^2) needs relatively lower compaction pressure than the unsewn preforms and the preforms stitched with lower thread tension (Figure 5.8a). Nevertheless, the bulge formation in the case of high stitch density plays a very vital role. Higher the stitch density higher is the bulge formation and this phenomenon is very critical for preform compaction.

Following the same trend of compaction, woven preforms sewn with high thread tension needs higher compaction pressure than the preform stitched with low thread tension. Furthermore, preforms sewn with low thread tension requires higher compaction pressure than the unstitched lay-up. Preform stitched with high thread tension needs maximum compaction pressure due to maximum bulge formation due to high stitch density.

Based on the above experiments, it can be stated that, for NCF preform compaction, combinations of high thread tension and higher stitch density or low thread tension and low stitch density have advantage over the unsewn preform. Whereas, for woven preforms, combination of low thread density and low thread tension is the optimum solution. Nevertheless, in general, low thread tension is preferable with the any magnitude of stitch density.

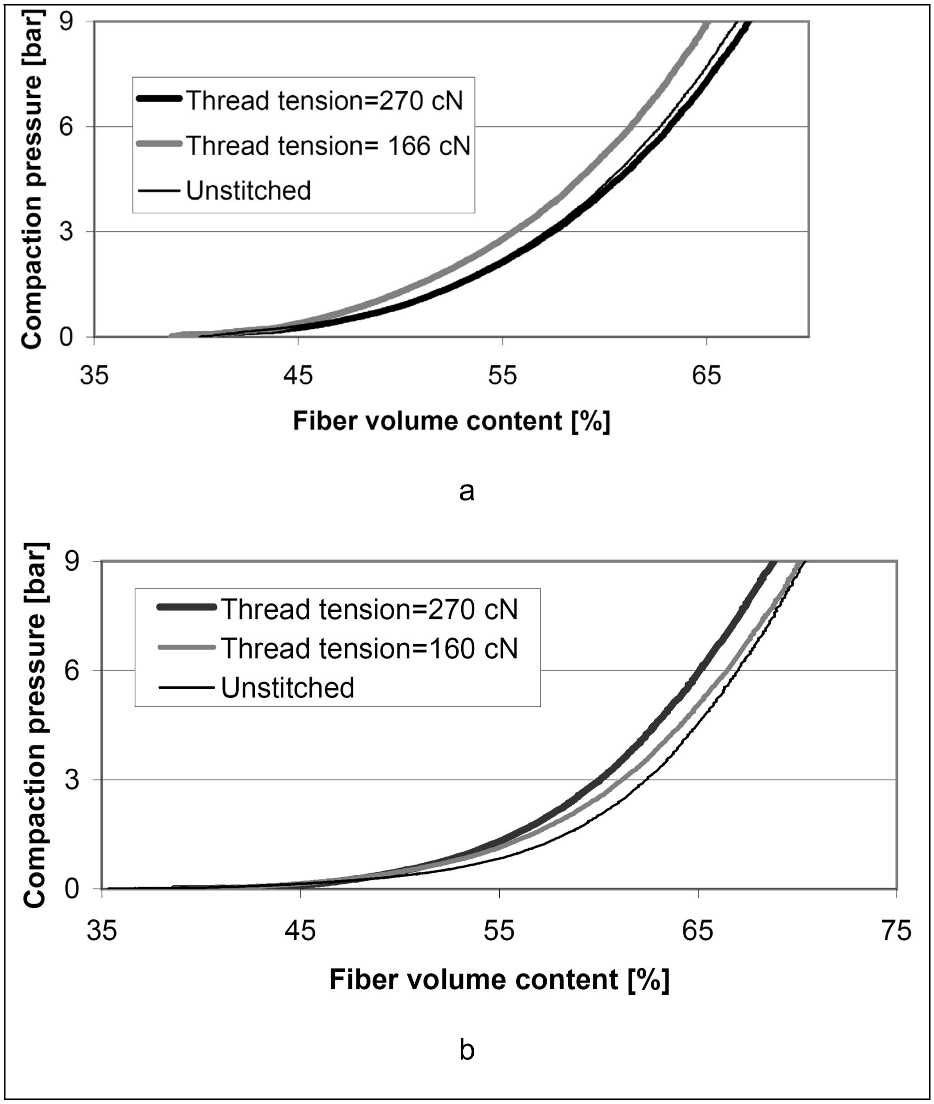

Figure 5.8: Influence of thread tension on sewn preform (stitch pattern: 5 mm x 5 mm, stitch density: 13.33 sttiches/cm^2, thread used: twisted multifilaments) a) NCF $[0/90]_4$ and b) 2/2 twill woven fabric $[0/90]_4$

5.2.2 Influence of applied stitch density

Figure 5.9 shows influence of stitch density on compaction behavior of four layers of sewn NCF and sewn woven preforms with high thread tension. At the initial level of compaction test, the pressure required to compress the NCF preforms is identical upto 52 % fiber volume content but as the test progresses, compaction curves differ from one another. Likewise, in case of woven preforms, the compaction behavior is similar till 49 % fiber volume content and then the curves fall apart from each other.

The results show that the NCF preforms sewn with high stitch density need a lower final compaction pressure (less displacement of measuring block due to high bulge) and the one stitched with lower stitch density needs higher compaction pressure (large displacement of measuring block due to low bulge, Figure 8.6).

In the woven preforms, a preform sewn with low stitch density requires less compaction pressure and one that sewn with higher stitch density needs higher compaction pressure. Here, due to flexible fabric construction, reinforcing fibers moves very freely on the application of force (during the sewing or compaction process). Nevertheless, sewing also arrests the fiber position, which is dependent on the selected thread tension and stitch density.

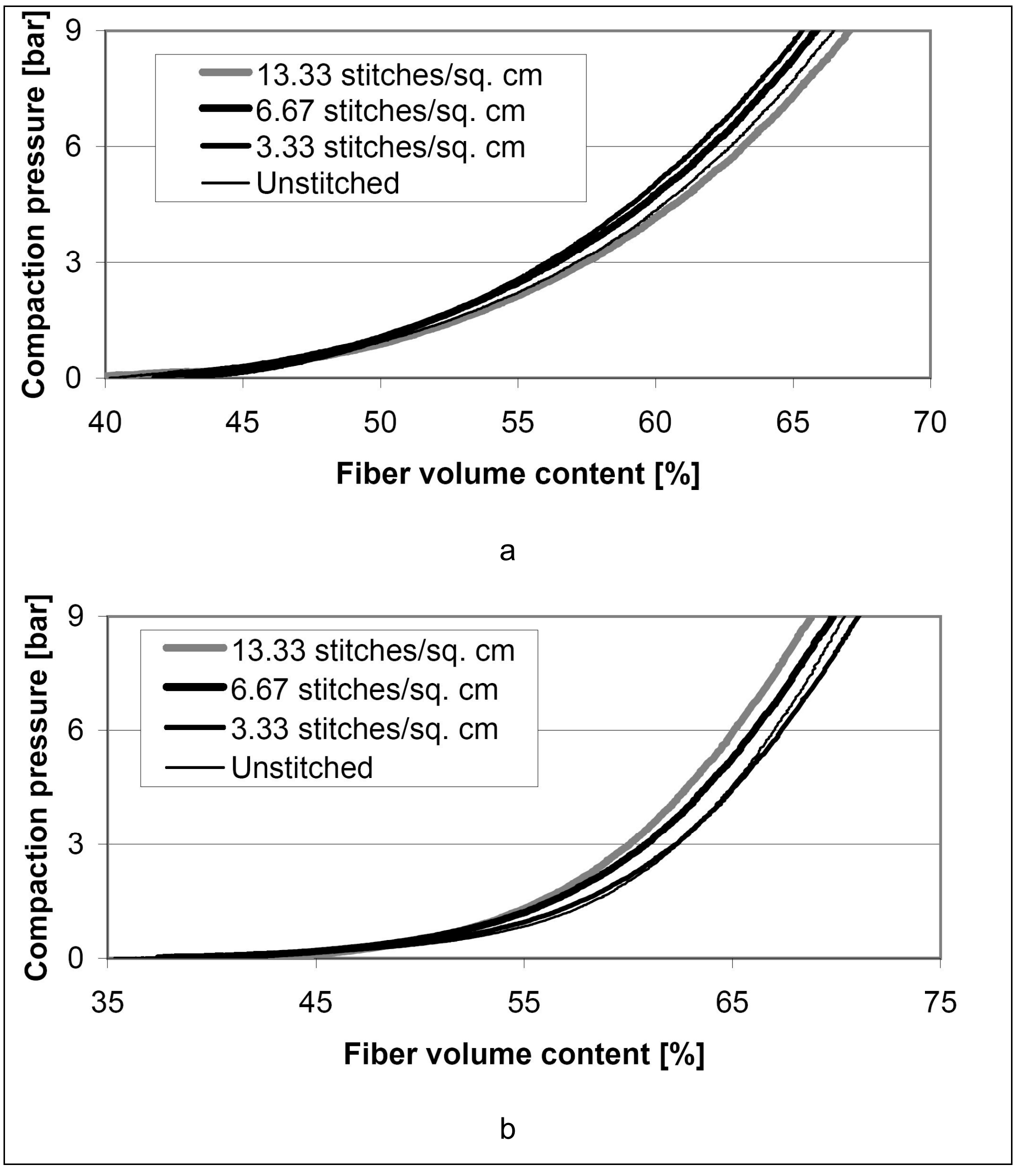

Figure 5.9: Influence of stitch pattern on compaction phenomenon (thread used: twisted multifilaments, material used: NCF, thread tension used: high) a) NCF $[0/90]_4$ and b) 2/2 twill woven fabric $[0/90]_4$

As mentioned before, as the fiber packages of the textile laminate are limited in their movements due to concatenation of seam at a certain level lead to a homogenous package thickness. However, it needs a high compression pressure to obtain a high amount of fiber volume, which depends on the stitch density. On the other hand, if preform is compacted to the final thickness, the tool loading can be simplified and compaction pressure required will be much lower at this stage.

5.2.3 Influence of type of fabric

Noncrimp and woven fabric preforms show varied compaction behavior. Figure 5.10 shows compaction curves for NCF and woven preform. Due to the absence of any roving waviness, the structure of NCF is very much compact than the woven fabric preforms. The chances of fiber redistribution in woven preforms are very higher because of the compression of crimped warp and weft. Whereas, only the trapped air between two layers is compressed in the case of the NCF preforms. This phenomenon complicates the redistribution of fibers in NCFs. Densely packed fibers in noncrimp fabric is a challenging factor for further compaction of preform. Figure 5.10 shows that, at the initial phase of the preform compaction, NCF preform require lesser compaction pressure due to compact arrangement of fibers (precompaction of NCF and woven fabric was 43.3 and 34.2 fiber volume percent respectively). However, as the compression process progresses, force required to achieve desired fiber volume content is higher than that of woven preforms.

In case of the woven preforms, comparatively moderate compression can be achieved due to rearrangement of fibers and reduction in warp and weft crimp, whereas, NCF shows more difficulties in fiber rearrangement. The final fiber volume content in both the cases was approximately same. However, it can be observed from Figure 5.10 that NCF gives relatively steeper curve and woven fabric offers saggy curve.

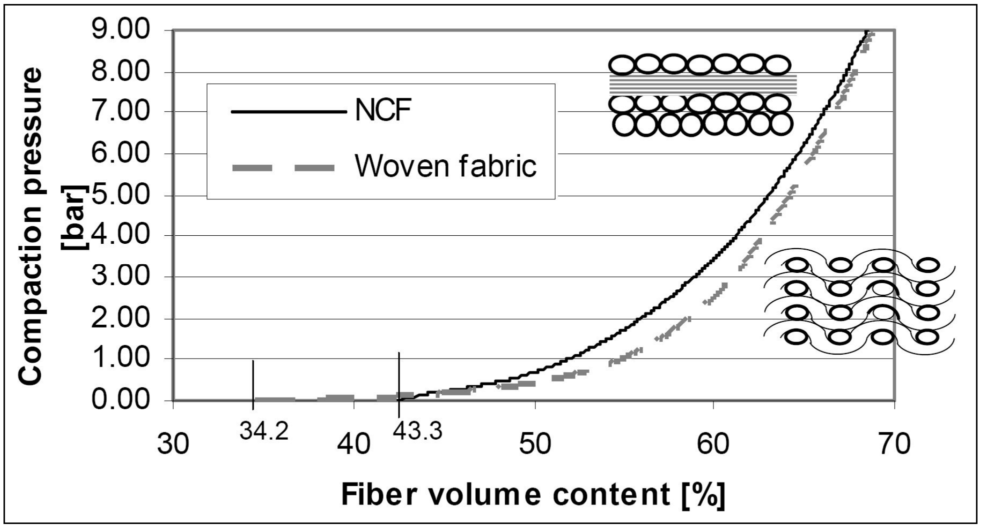

Figure 5.10: Fiber volume contents with respect to applied pressure, $[0/90]_4$ NCF and $[0/90]_4$ 2/2 twill woven fabric

5.3 Modes of preform compaction

Figure 5.11 shows a generalized graph on effect of pressure on fiber volume fraction. Here, the compaction curve is divided into four zones: linear zone 1 (L1), non linear zone 1 (NL1), non linear zone 2 (NL2) and linear zone 2 (L2). Each zone was further analyzed for its significant contribution towards type of compaction, porous compaction, fibrous compaction, or mixture of both.

L1 represents the preform compression behavior at very initial stage. This zone corresponds to the quick compaction, in the case of the unstitched preforms it is mostly porous compaction [97], but in the case of stitched preforms a very small amount of fibrous compaction (within roving) and the large amount of porous compaction (between roving) may takes place. It is possible to divide the curves into four basic zones and approximations for start up of each zone. In the case of unstitched lay-up, the approximations for initiation of linear deformation were also possible. All the zones were stated clearly, naming: nonlinear and linear porous compaction, nonlinear and linear fibrous compaction, and linear deformation. The NL1, which follows the initial linear compaction, is the critical zone, which corresponds to porous compaction in unstitched preform and equal amount of porous and fibrous compaction in stitched panel. Again in case of stitched panel, the bulge like contour, which was formed during sewing, starts to get compressed within this zone.

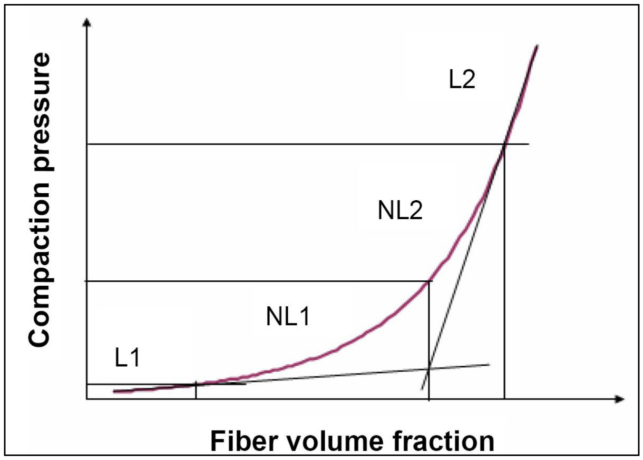

Figure 5.11: Phases of compaction

The real fibrous compaction of unstitched lay-up starts at NL2 and in the same zone fiber rearrangements starts in the stitched preform. As all the boundaries of unstitched fabric lay-up are free to move, within this zone, linear deformation of unstitched preform may occurs. Nevertheless, due to mesh-like sewing, localized blocking of fiber movement takes place, which restricts linear deformation of the complete panel.

L2 is a fibrous compaction zone for both the unstitched and stitched preforms. Here, both the preforms needs same amount of pressure for fibrous compression but the pattern of compression graph differs significantly.

The gradient calculations of each zone clarify the compaction behavior and nature of compaction (Figure 5.12). The compaction in the thickness direction is an obvious phenomenon in both the stitched preform and unstitched lay-up. In the unstitched lay-up, during the fibrous compaction, the deformation in length direction is a sub-effect of fiber rearrangement. In Figure 5.12, X denotes preform dimension and ΔX_1 and ΔX_2 denotes change in unsewn and sewn preform dimensions respectively. In the initial zone, L1, average slope (m) is much lower and as the compression progresses the average slope value at different compaction zones increases according to the type of compression. The fibrous compression in NL1 shows slight increase in the slope value. As soon as the further fibrous compaction starts, sudden increase in the slope was observed and curve become stiffer at the end where slope is maximum.

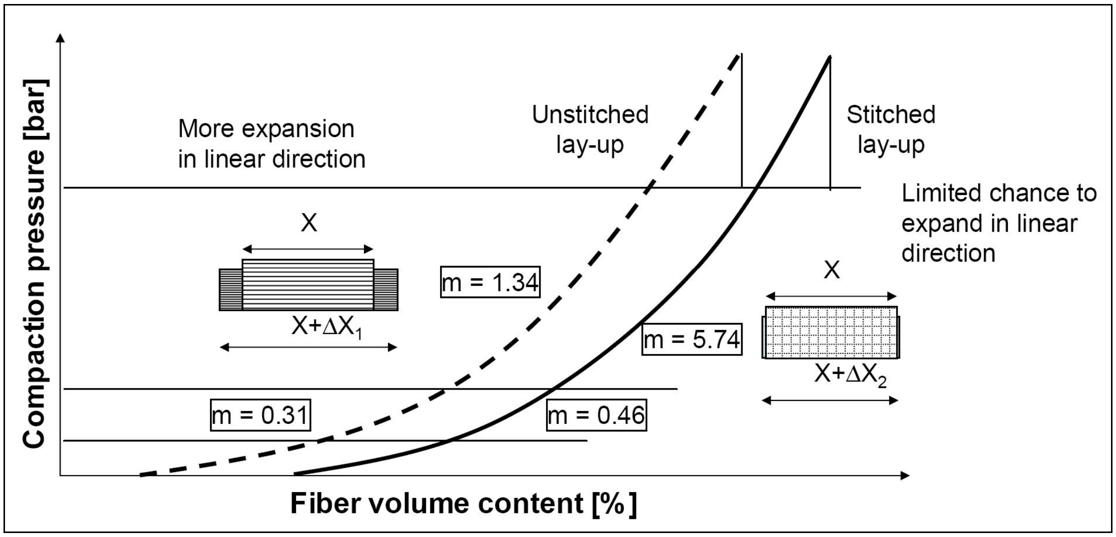

Figure 5.12: Average slope and deformation level for unstitched and stitched 2/2 twill woven preform (stitched preform curve moved apart by 15 % V_f on x scale to make a distinction), 6.67 stitches/cm^2, low thread tension

Due to the warp and weft linear deformation, a change in preform dimension is often observed. Figure 5.13 shows typical linear deformation curves for woven fabric. Increase in warp and weft deformation causes increase in preform area and decrease in preform area weight. Decrease in preform area weight influence the fiber volume fraction of the composite laminate. Arresting the warp and weft deformation to the certain extent is a function of seam, which helps to maintain preform area and preform weight at the cost of higher compaction force.

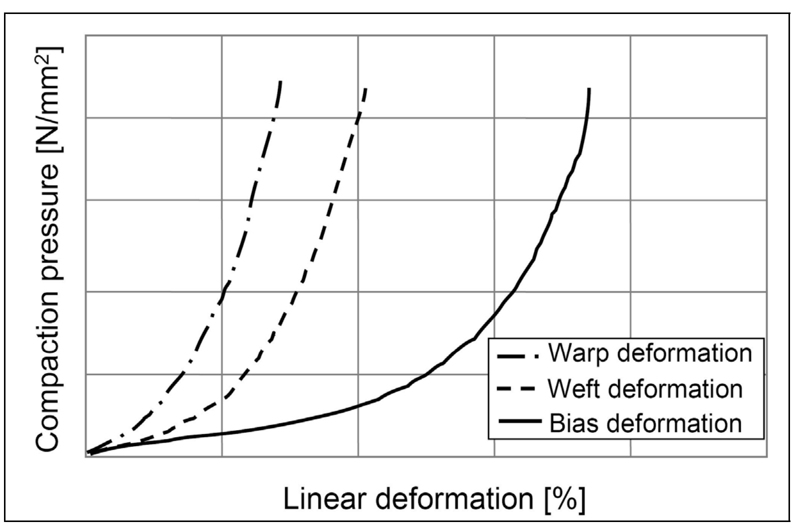

Figure 5.13: Influence of compaction pressure on linear deformation of woven fabric elements [100]

As shown in the Figure 5.14, the linear zones preform compaction is proportional to the applied pressure. In NL1, before the bulge compression, the fibrous compaction is much lesser (but not negligible to zero).

As the compression pressure increase the possibility of porous compaction reduces. The porous compaction at NL1 and NL2 varies in intensity. Allowed porous compaction, allowed fibrous compaction, linear deformation, and fiber displacement / rearrangement are the influencing factors during the preform compaction phenomenon. In NL1, the fraction of fibrous compaction is mainly corresponds to compression of wavy warp and weft rovings. The waviness of textile structure reduces its magnitude, which helps to increase total fiber volume content (which is again depends on possible linear deformation).

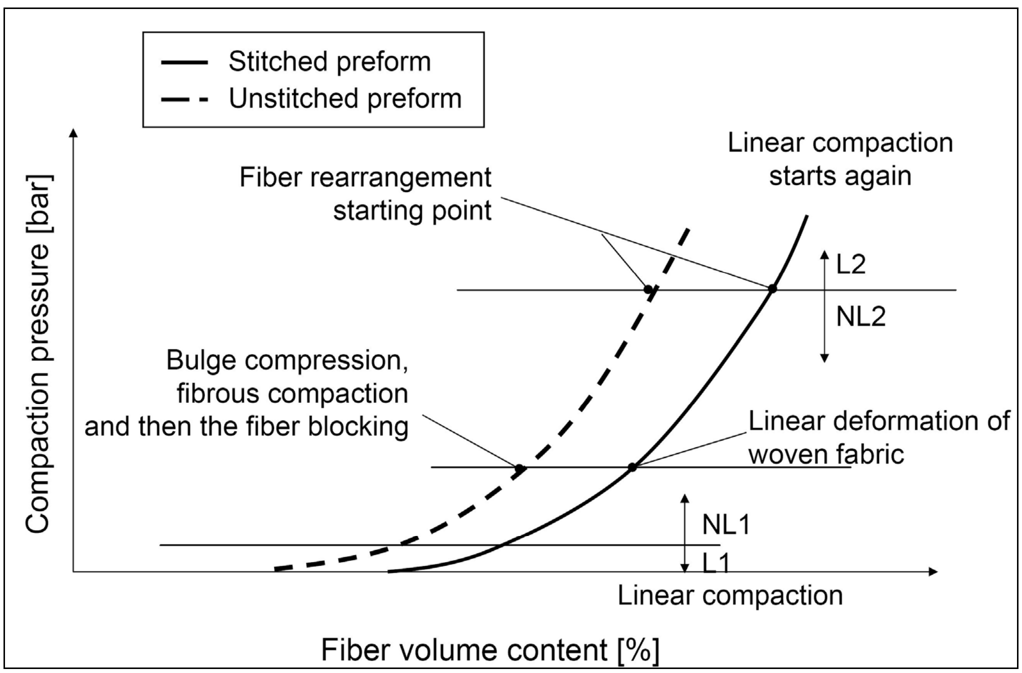

Figure 5.14: Compactions situations at stitched and unstitched preforms (stitched preform curve moved apart by 15 % V_f on x-scale to make a distinction), fabric used: 2/2 twill woven, stitch density: 6.67 stitches/cm^2 (medium), thread tension: low

In general, the porous compaction dominates the overall compaction phenomenon. At the end of linear compaction zone there is limited amount of pure porous zones, rather trapped pores present within the fibrous material. These trapped pores are being compressed in the NL2 at the cost of linear deformation. At the end of this zone, it is assumed that the possibility of porous compaction is nearly zero and can be neglected. As the maximum porous compaction occurs at NL1 (larger measuring block displacement), the total compaction at NL2 is very low (only fiber rearrangement). However, the compaction pressure necessary to compress the purely fibrous zone is much higher than the porous zone.

As shown in Figure 5.12, linear deformation of the fabric causes change in area which is a function of preform compaction and preform thickness. At the end of the NL2, if there is very limited possibility of change in fiber volume content after the application of further compaction pressure and if there is no positive control over the preform outer boundary, the applied force causes linear deformation of a preform. This phenomenon is responsible for reduction in preform thickness at the cost of increase in preform area, which is not allowed and expected during tool loading and composite manufacturing. To assess the quantitative values of these zones and to develop the generalizing equations, further analysis in terms of gradient at different zones of compaction was performed.

Linear regression - Gradient at different zones of compaction

From the compaction curves it can be stated that, compaction pressure (*P*) is a function of fiber volume content (V_f). To develop an equation for particular compaction zone in terms of *P* and V_f, general equation of linear regression is considered as a base:

$$y = bx + a \qquad \text{(eq. 5.1)}$$

Here, *x* is a fiber volume fraction and *y* is a compaction pressure taken from Figure 5.15a.

To generate equations of L1 and L2 for NCF and woven sewn preforms the above equation can be used. Values of *a* and *b* were calculated by using Eq. 5.2 and Eq. 5.3.

$$b = \frac{n\sum xy - \left(\sum x\right)\left(\sum y\right)}{n\sum x^2 - \left(\sum x\right)^2} \qquad \text{(eq. 5.2)}$$

$$a = \bar{y} - (\bar{x} \times b) \qquad \text{(eq. 5.3)}$$

According to eq. 5.1, equation for linear regression at linear zone 1 and 2, L1 and L2, are calculated:

L1 equation for sewn NCF preform compaction, $P = 0.08\ V_f - 3.33$ (eq. 5.4)

L2 equation for sewn NCF preform compaction, $P = 0.86\ V_f - 50$ (eq. 5.5)

L1 equation for sewn woven preform compaction, $P = 0.02\ V_f - 0.97$ (eq. 5.6)

L2 equation for sewn woven preform compaction, $P = 0.83\ V_f - 53.05$ (eq. 5.7)

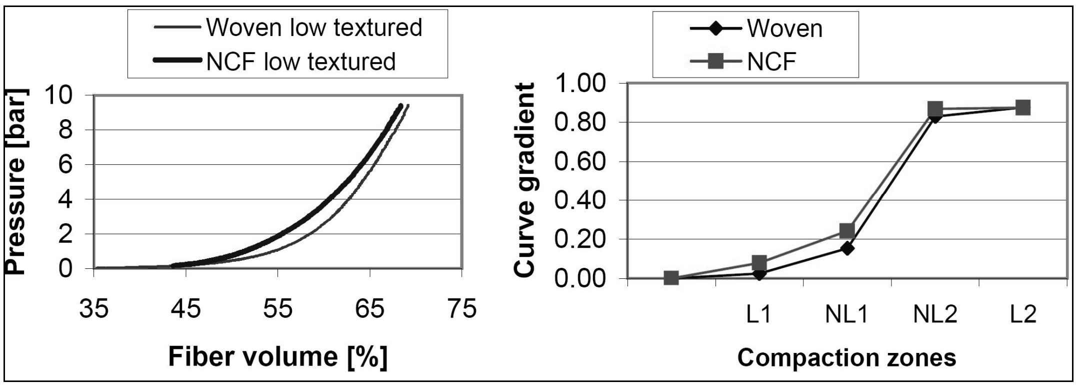

Figure 5.15: a) actual compaction curves and b) corresponding gradients. (preforms stitched by using textured thread, 90 cN thread tension, and 3.33 stitches/cm^2 stitch density)

Figure 5.15b show gradient curves illustrating L1, L2, NL1, and NL2. In this figure it can also be observed that, at the first linear zone, curve is nearly flat. In the non linear zones, gradient curve deviates sharply and at the end, for the second linear zone, the gradient approaches to one with flattened line. Based on the linear regression equation, coefficient of regression varies from 0-0.1 in the L1, 0.38 to 0.53 in non linear zones (considered as a line), and from 0.82 to 0.96 in L2. The analysis can conclude the simplistic approach of actual compaction behavior in the different zones.

5.4 Summary

Process of sewing delivers the opportunity to adjust FRPC manufacturing parameters as well the mechanical performance of a part. Different sewing parameters: stitch density, stitch pattern, and various stitch formation particulars can define the compaction of the fiber package. The compaction behavior of a stitched fabric stack dominates the fiber architecture and consequently determines mold placement phenomenon. Sewing parameters have to be selected with respect to thread used and lay-up of the reinforcing structures as well as the type of reinforcing fabric. In terms of quality, all these parameters need to be adjusted according to the specifications of FRPC part, tool loading, and injection process. Linear and non-linear compaction is a function of fiber volume and fiber packing during the compaction phenomenon. Phases of preform compaction illustrate fiber packing and force needed to achieve the final fiber volume content.

6 Analysis of laminates sewn with the epoxy compatible threads

The basic characteristics of polyester fibers (hydrophobic material) and its processing requirements have the limitations to use it in high performance FRPC applications. Furthermore, the geometry of the thread was one of the important factors of consideration, for impregnation of the entire sewn structures. Thus, the impregnation of polyester thread and rearrangement of fibrous geometry are the key points for the compatibility measures. A well impregnated thread improves the laminate structural properties. The main task of this study is to improve the compatibility of the polyester thread with resin system and LCM process. Furthermore, choosing a thread geometry for compact, easy to handle, and improved quality preform structure, another requirement, is adhered to the study.

Considering the process of sewing, the threads like Kevlar®, carbon, or glass requires high tension during the sewing; this may intensify the deterioration of preform quality and so the FRPC properties. Chapters 3 and 4 are focused on the investigations of preforming process using sewing technique. In this study, quality of preforming seam and assembly seam have been investigated and correlated with the laminate properties. The multi-textile preform fixing and positioning consist of compaction and stabilizing of reinforcing fabric lay-up that makes the preform stable for further handling during the preform assembling and tool loading. For such seams the involvement of the thread is considerably high. The high performance threads are not suitable to use for preforming as they are not flexible and very expensive. Polyester sewing threads, which are commonly used in conventional textile application, can be effectively used into the composite manufacturing process steps.

A polyester thread has number of advantages, e.g., easy availability, variety of geometries, varied fineness, and effectively low cost. To use this thread in fiber reinforced composites, the main prerequisite is, thread should be able to impregnate completely. However, hydrophobic nature of the polyester polymeric material and applied spin-finishes are the challenges to fulfill this requirement. Apart from that the thread should be compatible with the sewing process. As the polyester thread is commonly used for the garment manufacturing industry, it is possible to sew with this thread at very high speed and with optimum machine parameters. The selection of finest possible thread, that is compatible with the automated sewing operation, is again a point to be considered. The threads for preform sewing were selected according to the constructional geometry, openness (bulk), linear density (tex), and resin impregnation capacity. Thus, compatibility of the polyester thread with matrix is the most important factor which needs further investigations. By removing the commercially applied spin-finish and silicon oils from the polyester thread it can be made free from any external coatings. To improve the functionality of a thread and matrix compatibility, an additional epoxy compatible sizing on the washed thread should be applied.

In this chapter, an experimental work for qualitative and quantitative analysis of sewn preforms and the laminates made thereof is outlined. Physical tests were performed to observe the physical properties of the laminate. Microscopic observations of the sewn preforms, impregnated laminates, and failed specimens were also carried out. Bonding between polymer matrix and polyester thread is investigated by the examination of thermal behavior of stitch regions where majority of polyester thread is involved in the laminate.

6.1 Materials and experimental

The experiments were designed to analyze the performance of different polyester threads in the FRPC laminate. The test panels used were manufactured from 4 layers of 5-harness (5H) satin fabric (fabric area weight 370 g/m^2). For sewing purpose, four different threads were used (see section 3.2): 1) epoxy compatible twisted multifilaments (23 tex) named A, 2) epoxy compatible core spun thread (22 tex) named B, 3) epoxy compatible textured thread (13 tex) named C, and 4) untreated textured thread (13 tex) named D.

Flat panels with the lay-up construction of $[0/90]_4$ measuring 220 mm x 180 mm were stitched together. The stitch pattern employed in the specimens was ± 45° having stitch length of 3 mm and stitch density of 13.33 stitches/cm^2. Selected cross stitch pattern is generally used for the fixation of preforms with 0°/90° fiber orientation in the fabric structure. The reason behind the selection of dense stitch pattern was the small dimensions of testing specimens. This method is used to observe the effect of stitches and sewing thread on laminate properties. Here, the specimen contains enough number of stitches per unit testing area. A modified lock stitch was used to sew the panels.

Unsewn and sewn preform panels were injected with epoxy matrix through the VARI process. After the completion of injection process, the composite laminate is allowed to cure at 80 °C for 5 h. The manufactured laminate plates were then used for the specimen preparation.

6.2 Testing and results

Testing of stitched composite laminates was performed to evaluate the influence of preform sewing. The experimentation was not focused on the actual TTT performance of the stitched laminate, but it is focused on the level of polyester impregnation and its contribution towards the laminate properties. Laminate compression test, interlaminar shear strength, and flexural bending strength were performed to investigate the role of joining seams in the properties of composite laminate. Though the main aim of these types of seam is not TTT reinforcement, the additional advantage of the seams was investigated through this testing program. Each sample was tested with 7 specimens and 5 middle readings were selected for further analysis.

6.2.1 Compression testing

The test was performed according to the DIN EN 6036 [101]. The Zwick 1485 with compression testing attachments was used for the testing. A loading rate of 0.5 mm/min was used for all specimens. The applied load and the axial displacement between the two gripping points were measured with a computer data logger. A plot of force vs. displacement was the outcome of this test (Figure 6.1). Force required to rupture the specimens were plotted for differently stitched panels and unstitched laminate as well.

In Figure 6.2, comparative compression strength of stitched and unstitched laminate is clearly indicated. In general, the compressive strength reduces after sewing [102-105] but in this study the polyester thread used was treated with epoxy compatible sizing which helps to increase thread matrix bonding. Apart from that, the influences of the thin polyester thread are negligible on the preform structure, rather it influence positively on the laminate strength.

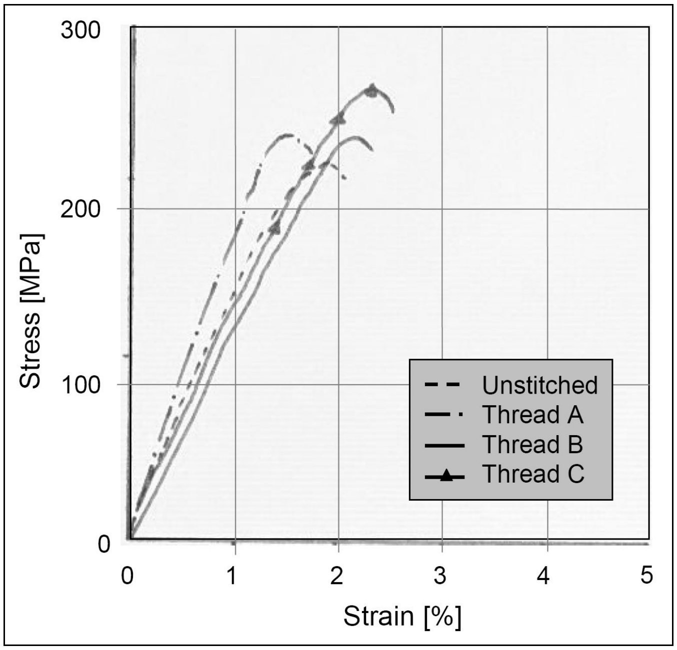

Figure 6.1: Plot of the applied compressive stress vs. compressive strain for unstitched and stitched specimens

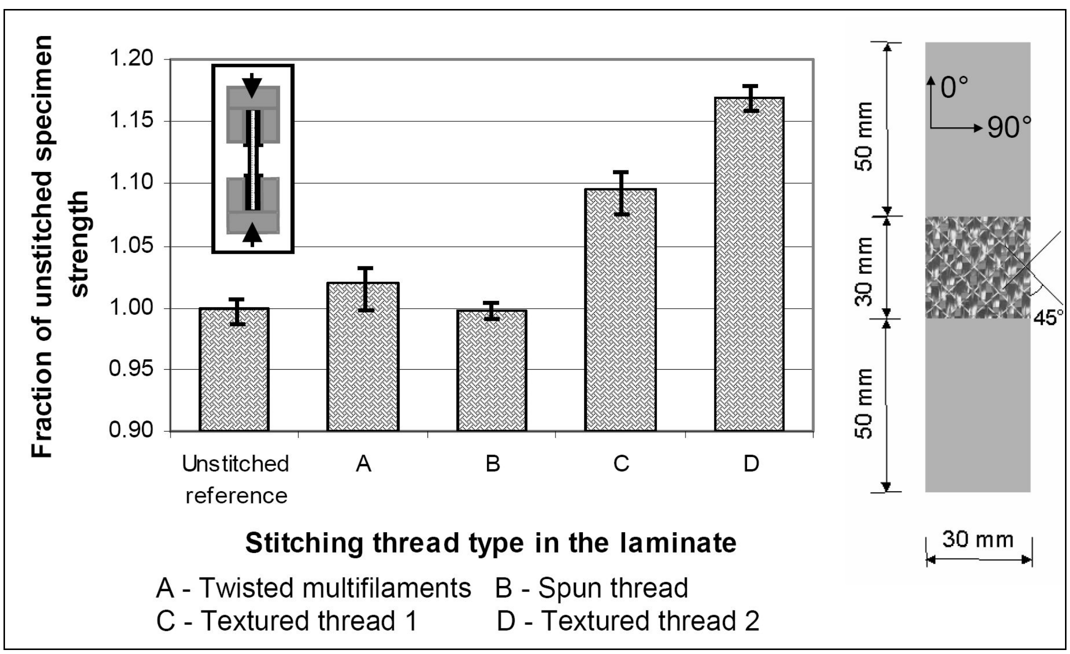

Figure 6.2: Compressive strength comparison

6.2.2 Three point bending test (3PB)

Interlaminar shear strength (ILSS) was examined according to the DIN EN 14125 standards and testing instrument with short beam testing attachment was used for the experiments. As the specimen dimensions required for the test were very small, special precaution was taken during the sample preparations. The data collected from the software was in the form of a plot of bending strength vs. displacement. By using the specimen specifications, the ILSS values were calculated for all the samples and compared with each other. The ILSS calculations were based on eq. 6.1.

$$ILSS = \frac{3 \times P_R}{4 \times t_s \times w_s} \qquad \text{(eq. 6.1)}$$

where:

ILSS = interlaminar shear strength (MPa)

P_R = rupture load (N)

w_s = width of specimen (mm)

t_s = thickness of specimen (mm)

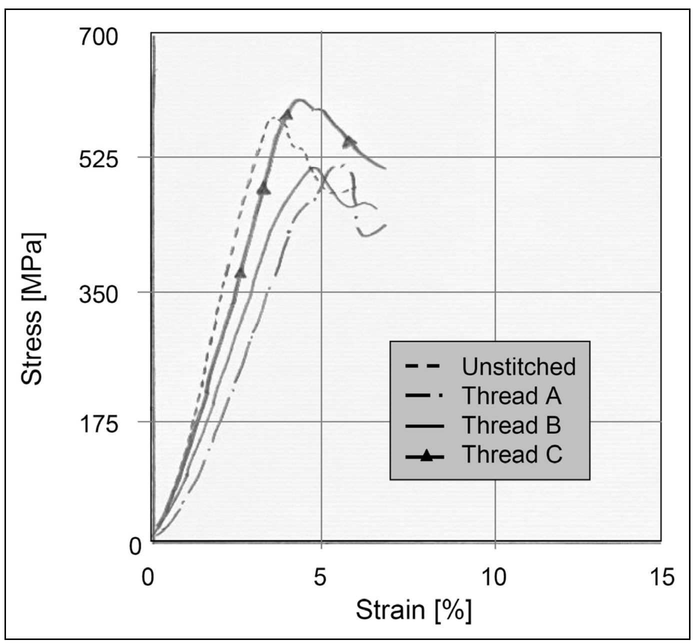

Figure 6.3: Bending behavior plots of the bending stress versus bending strain for unstitched and stitched specimens

Due to very short span length of the specimen and high stitch density (27 stitches/specimen area), the micro disturbances in the fiber orientation (due to sewing) influences the macro scale of the laminate.

Figure 6.3 shows typical stress vs. strain curves for unstitched and stitched laminates. Thread A and B shows lesser stress values but the laminates are more elastic. The laminate stitched with thread C shows more fails at higher stress values and strain values are also more than the unstitched laminate. Figure 6.4 shows the comparative graph of ILSS values and here, in general the unstitched laminate shows superior performance over the stitched laminates. Nevertheless, it is possible to obtain the ILSS values similar to unstitched specimens by using specific sewing thread.

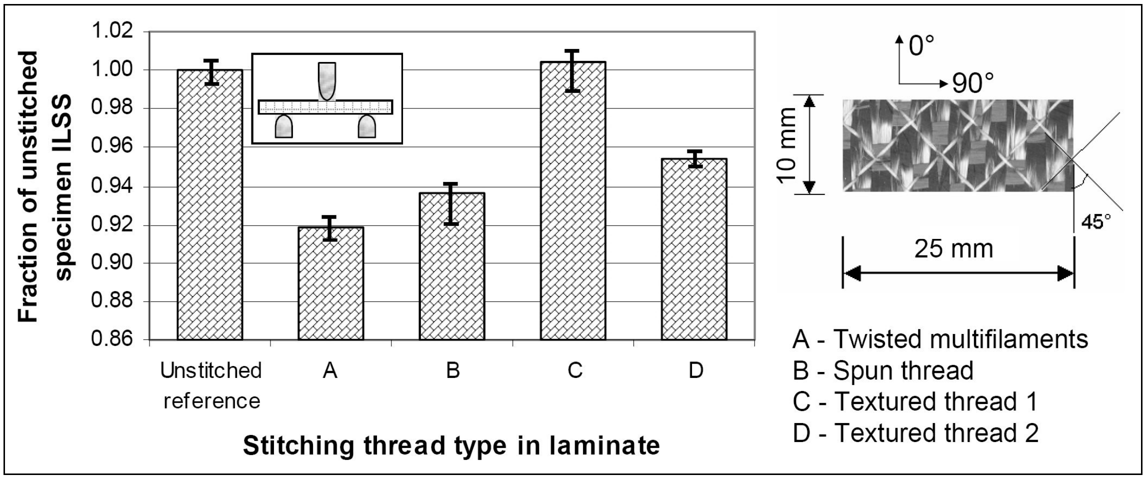

Figure 6.4: Interlaminar shear stress (ILSS) comparison

6.2.3 Flexural bending test

This test helps to analyze the bending stiffness of laminate. The test was performed according to DIN EN 14125 standard and by using same testing instrument used for 3PB with fixtures attachment for flexural bending test. In this test as well, 7 specimens were tested and considered 5 for the further analysis. Data obtained from the machine is in the form of curve between bending strength and flexural displacement. Figure 6.5 shows the bending strength of stitched and unstitched laminates. The flexural strength was calculated by using eq. 6.2:

$$FS = \frac{3 \times P_f \times l}{2 \times t_s^2 \times w_s} \qquad \text{(eq. 6.2)}$$

where:

FS = flexural strength, MPa

P_f = failure load (N)

l = support span, (mm)

w_s = width of specimen (mm)

t_s = thickness of specimen (mm)

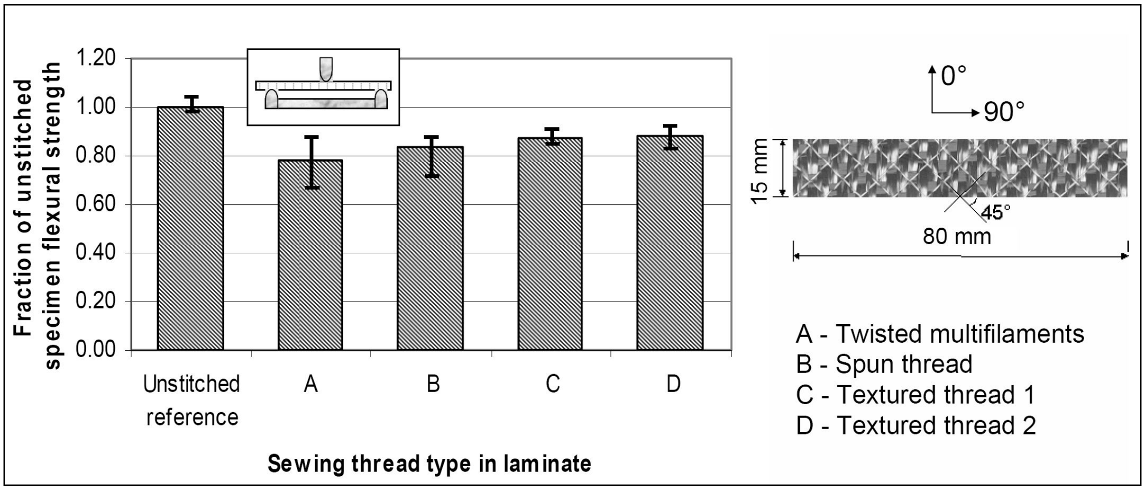

Figure 6.5: Flexural strength comparison

After sewing, flexural strength of the laminate reduces up to 21 % (in case of the twisted multifilaments). Nevertheless, textured threads show relatively better performance than the other two types of threads. Furthermore, it has also been observed that epoxy matrix compatibility of a thread does not play a vital role in flexural strength values.

6.2.4 Microanalysis of specimens

Preform and impregnated panels were analyzed in micro scale in order to correlate the influence of sewing on the quality and properties of the FRPC. The stereo microscopy was used to analyze the structure. The analyses were mainly based on the stitched zone, seam appearance and role of seam in mechanical performance of the laminate.

Microscopic analysis of the stitched zone was performed to visualize the stitch geometry inside the laminate, thread impregnation, and degassing of lubricant material inside the laminate (air bubbles).

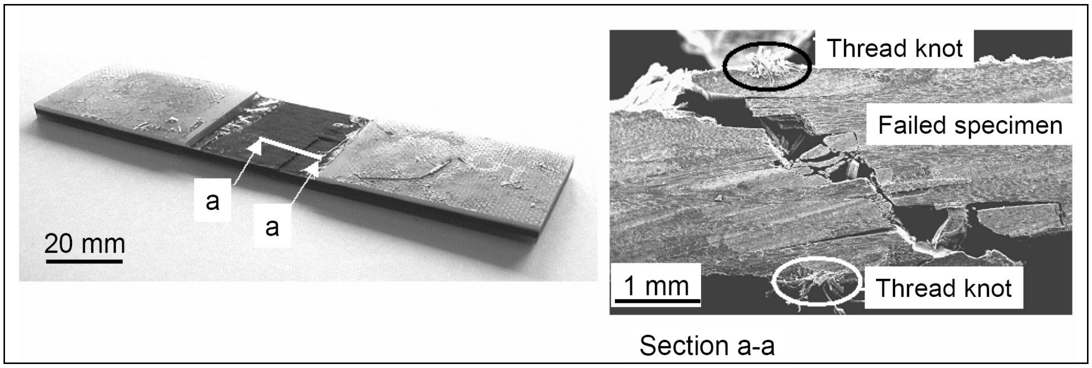

Figure 6.6: Micrograph of compression failed specimen

To visualize the behavior of ruptured laminates after the tests, those specimens were also analyzed in microscopic scale. Due to the formed stitch the displacement of the fiber is clearly visible which does affect on the bending strength of laminate as well on the ILSS. The resin rich area at the stitched zone causes the minimization of physical strength of the laminate. Figure 6.6 and Figure 6.7 shows the micrographs of specimen failed after the compression test and 3PB test respectively. Because of the sewing thread, the laminate failure strength increases slightly and thus the negative effect of the resin rich zone is nullified. In the case of short beam shear test (3PB) crack propagation is restricted because of the crossed thread but it is not enough to negate the influence of fiber disturbances.

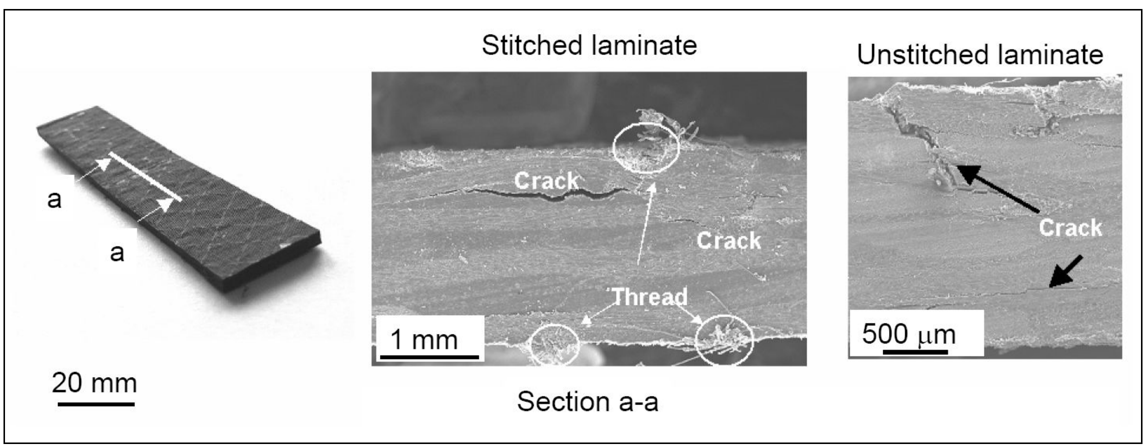

Figure 6.7: Micrographs of failed specimen (after ILSS test)

6.2.5 Thermal behavior of impregnated thread

Differential scanning calorimetry (DSC) was used for the thermal analysis of the specimens. The significance of this test was to examine the sustainability of the polyester thread inside the laminate, influence of fluid matrix system on the thermal behavior of thread, and thermal behavior of complete laminate. Finally, this tests may help to correlate thread matrix interaction and mechanical properties obtained thereof. A very small specimen (20 mg), representing just a stitch-hole was selected for the test of thread matrix interaction and tested for the melting temperature (T_m). The test was performed from 20 °C to 300 °C temperature range with the heating rate of 5 °C/min in the nitrogen atmosphere.

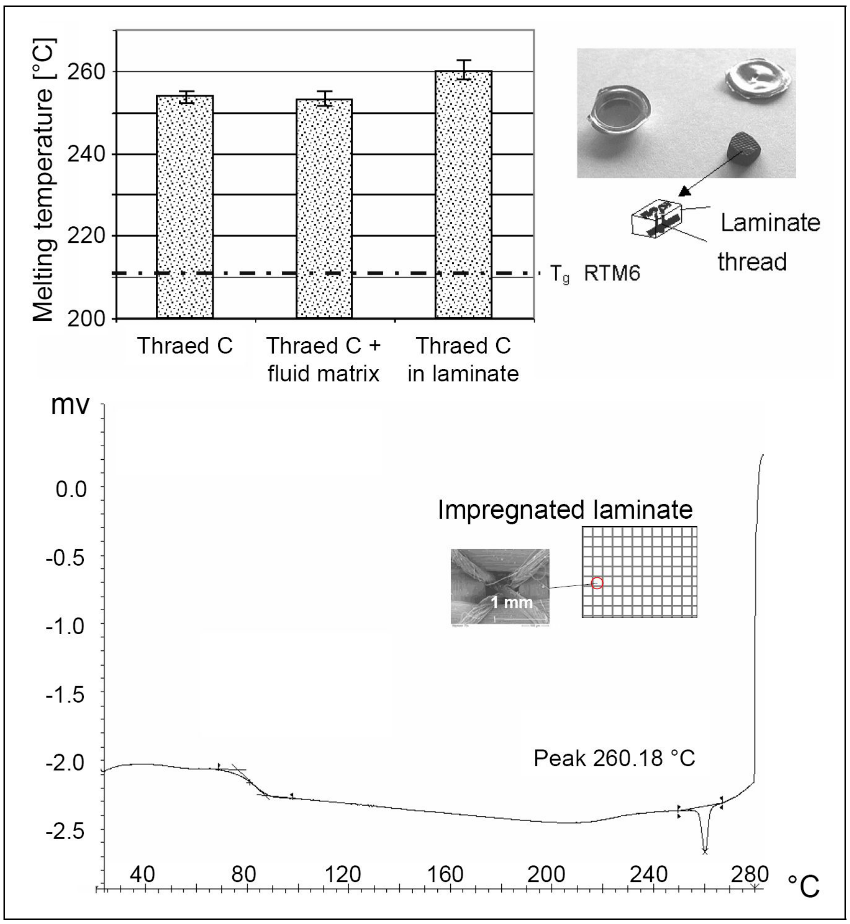

Figure 6.8: Influence of thread matrix bonding on melting point of polyester

Figure 6.8 shows the specimen size and a graph of melting temperature of polyester thread at different conditions. The increase in the thread melting point is an indication of good thread matrix interaction. Poor thread matrix interaction make no change in the T_m of the polyester thread (it corresponds to 250 ± 3 °C). The impregnation of polyester thread and corresponding increase in the melt temperature may allow using polyester polymer threads in the high performance applications.

The polyester threads used for the tests were treated with the special epoxy compatible sizing. Thus it improves the thread matrix interaction which helps to achieve better mechanical properties of the stitched laminates (specifically in the compression strength of the laminate).

6.3 Summary

In preforming seam, since the thread remains in the reinforcing fiber architecture but it does not carry any structural load of the FRPC part, the negative influences of the thread inside the laminate have to be minimized. Sewing thread design and geometry had significant effect on the quality of the preform, FRPC processing, microstructure, and properties of the laminates. Furthermore, impregnation of the thread is a key factor for reducing negative effects on mechanical and thermal properties of the FRPC. Therefore, the sewing thread material and influence of the sizing are well studied. It is found that the textured single threads are the most suitable yarns in order to improve mechanical and thermal characteristics of stitched laminates. However, these threads have to be improved in terms of applicability in highly automated sewing plants.

7 Experimental investigations of high performance threads

Application of high performance threads in the preforming application is very well studied by various researchers. Nevertheless, the optimum solution for TTT reinforcement with minimum influence on the in-plane mechanical properties and suitable sewing threads for the high speed sewing machines are not well explored. Recently, various carbon fiber threads which are compatible with the liquid matrix system and other high performance threads like PBO, aramid, etc. which are partially compatible with liquid matrix are readily available in the market. The improvements for high speed applications of carbon fiber threads and matrix compatibility of PBO and aramid (especially Kevlar®) threads are not yet well examined. Furthermore, comparison between emerging high performance threads like PBO and carbon fiber threads is essential for wide spread preforming application with reduced production time.

In this Chapter, the experimental investigations on the effect of through-the-thickness sewing on the microstructure and mechanical properties of the composite laminate are discussed in detail. Composite single-lap joint test of glass fiber reinforced polymer composite stitched with E-glass and CF-1 carbon fiber thread is performed as a separate study. Interlaminar shear stress and flexural bending strength of CF-1, CF-2, and PBO stitched NCF laminates are also evaluated. An unstitched reference samples were tested to examine the influence of sewing.

7.1 Single-lap joint test

Adhesively bonded composite lap joints are widely used in various aerospace components. Number of researches has proved that the through-the-thickness sewing in Z-direction can significantly improve the mode-I and mode-II delamination toughness of laminated composites [1, 10, 13, 23, 24]. The influence of sewing on the strength of composite is quite interesting and various researches presented data on Kevlar® stitched lap joints. Aymrich et al. commented that sewing does not improve the static strength of joints, but significantly extends both the crack initiation and crack propagation phases. The extension of the delamination growth stage, in particular, was attributed to the bridging action of stitches on delaminated adherents, which suppresses the mode-I component of strain energy release rate and thus reduces crack propagation rates [106]. Furthermore, the other researches explains that sewing improves the single lap strength of stitched laminate by 18-38 % [107-

109]. In the present study the effect of type of thread and sewing density on the glass fiber NCF laminate has been observed.

7.1.1 Experimental

In the present study, the performance of stitched and unstitched single lap joints has been assessed. The test panels used for the experimentation were manufactured from glass fiber NCF, ±45°, from Saertex GmbH & Co. KG and epoxy matrix (Huntsman LY564 + HY 2954 [110]) via RTM technique. A ±45° fabric material was cut to get 0/90 fiber orientation before manufacturing the panels. For purpose of sewing, a twisted 68 tex (2 x 34) glass thread and a 1K (67 tex) based carbon fiber thread (IVW-CF) were used.

Single-lap joint with an overlap length of 25 mm and measuring 250 mm x 200 mm were first formed by overlaying four [0/90] fabric stacks. The stitch pattern employed in the stitched specimens was in 90° to the testing direction, having varied stitch length (sl) of 2 mm and 4 mm, and stitch width (sw) of 5 mm (stitch density of 5 stitches/cm^2 and 10 stitches/cm^2). A modified lock stitch was used to sew the joints.

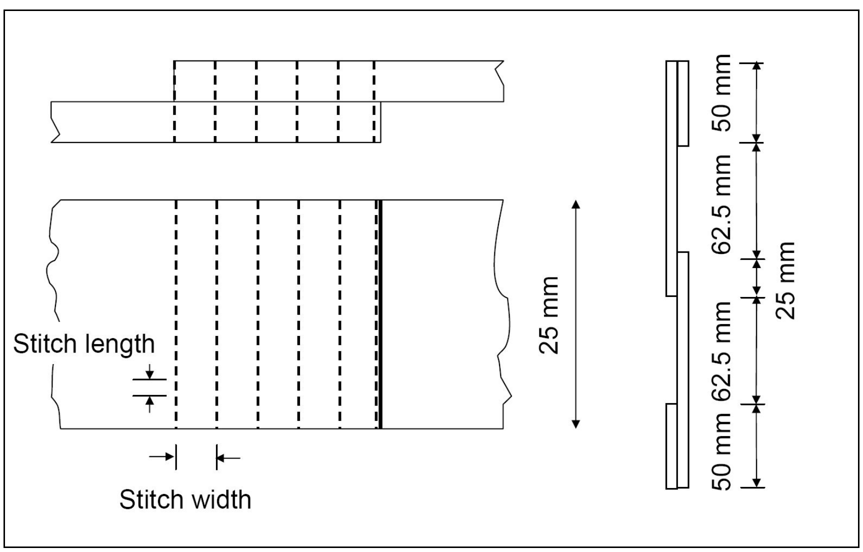

Figure 7.1: Schematic diagram of a stitched single lap joint and configuration of specimen for tensile testing

The resin impregnation technique used was vacuum assisted resin infusion (VARI). After the injection, the composite was allowed to consolidate under 0.1 m bar vacuum and a cure temperature of 80 °C for 2h. All panels were then post cured at 160 °C for

4 h. Spacers were used in the lay-up to ensure that the required specimen profile and thickness were obtained.

All the specimens cut to the required width of 25 mm, the average specimen width was 1.82 mm and average fiber volume content was 49.2 %. The specimens were prepared according to Figure 7.1.

The specimens were tested in tension on a Zwick 1485 testing machine at room temperature. A loading rate of 1 mm/min was used for all specimens. The applied load and the axial displacement between the two gripping points were measured with a computer data logger. DIN EN 1465 [111] standard was used for the testing and strength values were calculated by using following equation (eq. 7.1):

$$Lap\ strength = \frac{F_{max}}{L_o \times w_a} \qquad \text{(eq. 7.1)}$$

where:

F_{max} = maximum force in N,

L_O = overlap length in mm,

w_a = average sample width in mm,

7.1.2 Results and analysis

The measured axial loads increased almost linearly with axial displacement of all specimens. For all specimens, failure occurred at the overlapped section; in addition, sewing thread fracture was clearly observable. The effect of stitch density and type of thread used on the join failure is shown in the Figure 7.2. Here, stitched specimens shows increased tensile strength compared to the unstitched one. Furthermore, low stitch density specimens show increase in strength than the densely stitched specimens. As far as the sewing threads are concerns, a carbon fiber thread gives higher strength than the glass fiber threads.

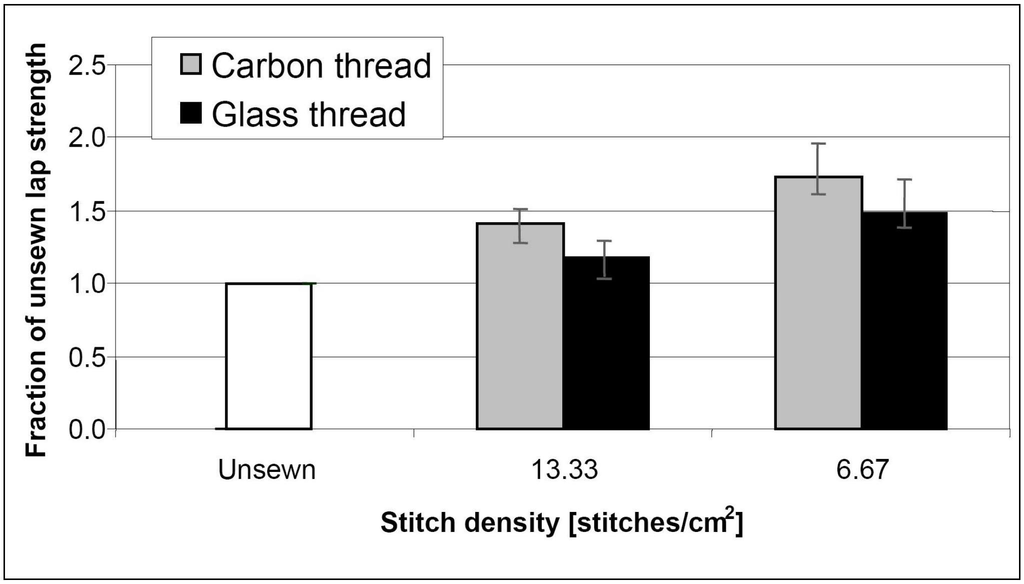

Figure 7.2: Relative single lap tensile strength of stitched laminates

The observed results indicates that the tensile strengths of the glass fiber sewn single-lap joint specimens were over 40 % higher than the unstitched specimen and the strength of carbon fiber sewn specimen increased by up to 70 %.

Influence of thread type

Glass fiber sewing thread is much more flexible than the carbon fiber thread. It is also observed from the reported literature on related studies that the thread stiffness has influence on the lap strength; the results obtained within this study also shows similar findings. The difference between the strength of carbon fiber sewn joints and glass fiber sewn joint is approximately 30-32 %. However, change in stitch density has no influence on these characteristics.

Influence of stitch density

Densely stitched joint has double the number of sewing threads as compared to joint with lower stitch density. But, the difference between the strength of such joint is 22-25 % only. It means the lap joints with low stitch density shows higher strength than the joints with high stitch density. This difference is independent of type of sewing thread used. About this finding, different views of other researches are presented in literature [107, 109].

7.2 Laminate bending and shear properties

Damage tolerance of epoxy polymeric composites can be enhanced by improving the interlaminar properties which can be done by toughening the matrix and/or by using TTT reinforcement. The sewing technology is competent enough to develop preforms with higher interlaminar strengths [112]. The performance of stitched preforms was verified by analyzing the mechanical performance of polymeric composites through flexural and shear tests.

Flexural and interlaminar shear strengths of continuous fiber reinforced composites are usually performed to characterize these materials due to the ease of specimen preparation and testing. Gripping, buckling, and end tabbing are not issues for these types of tests [113, 114]. In flexural tests, beams with a small span-to-thickness ratio (L/h) are dominated by shear and beams with long spans fail in tension or compression.

In general, the shear failure is affected by the same factors as the transverse tensile strength, because shear stresses and strains become concentrated in the matrix between fibers in a similar manner to that outlined for transverse tensile. However, there is more scope for the local matrix deformation, without occurrence of any crack. Under shear stress, the local stress concentration is relaxed more readily [113].

In this study, flexural and shear strengths of TTT stitched laminates impregnated with aerospace grade epoxy matrix were evaluated. The main purposes were quality control, data evaluation, and comparative testing.

7.2.1 Experimental

The test panels used for the experimentation were manufactured from noncrimp carbon fabric (a: -45/0/+45, b: +45/0/-45, c: 90/0/90) from Saertex GmbH & Co. KG and epoxy matrix from Hexcel corporation (RTM 6 [115]) via RTM technique. For the purpose of sewing, carbon fiber threads (CF-1: IVW-CF thread and CF-2: CF thread based on winding technology, see section 3.2) and PBO threads were used. Figure 7.3 shows used NCFs with different lay-up configurations.

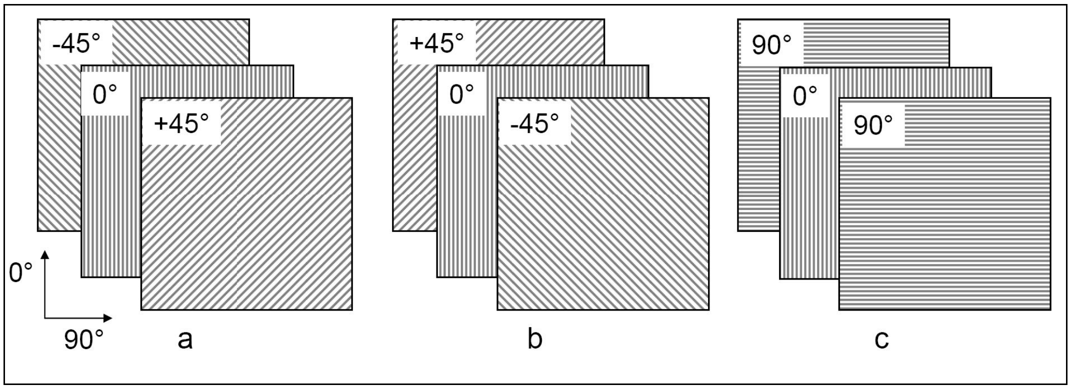

Figure 7.3: NCF used for preform manufacturing

As discussed in the previous sections, the experimental studies on the sewing process can help to set machine parameters at the optimum limit, which assists to produce good quality preforms. The preforms measuring 220 mm x 180 mm were first formed by overlaying $[a/b/c]_s$ stacks (Figure 7.3). The stitch pattern employed was in 0° fiber direction, having a 2.5 mm stitch length and a 2.5 mm stitch width (stitch density: 16 stitches/cm^2). A modified lock stitch was used to sew the preforms.

The resin impregnation technique used was vacuum assisted resin infusion and the injection was completed at 120 °C. After the injection, a composite laminate was allowed to consolidate under 0.1 mbar vacuum and at a curing temperature of 160 °C for 75 min. All panels were then cured free standing at the temperature of 180 °C for 2 h. Specimens were cut at 0° and 90° to the sewing direction.

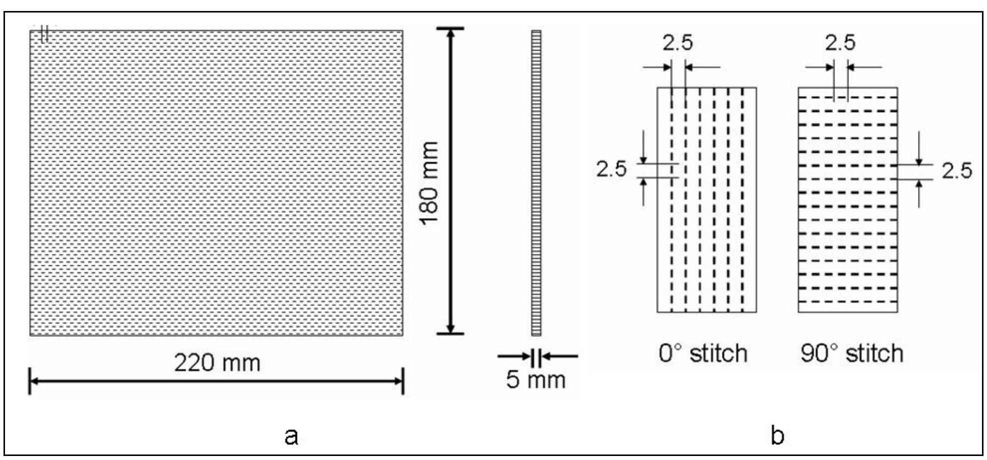

Figure 7.4: a) panel stitched and impregnated for testing; b) specimens cut in parallel and perpendicular to stitch direction

Shear tests

The interlaminar shear tests (ILSS) were carried out according to DIN EN ISO 14125 method. At least seven specimens (short beam: 25 mm x 10 mm x 5 mm) of each laminate family were tested and an appropriate device was used for the shear tests on the Zwick-1474 machine. A loading rate of 1 mm/min was used for all the specimens. The applied load was measured using a computer data logger. The ILSS calculations were based on eq. 7.2.

$$ILSS = \tau = \frac{3 \times P_R}{4 \times t_s \times w_s} \qquad \text{(eq. 7.2)}$$

where:

$ILSS$ = interlaminar shear strength (MPa)

P_R = rupture load (N),

w_s = width of specimen (mm),

t_s = thickness of specimen (mm).

Flexural bending tests

The flexural tests were carried out according to DIN EN ISO 14125 (3-point loading) [114], using a minimum of seven specimens (dimensions: 100 mm x 15 mm x 5 mm) for each laminate family. These tests were performed on the Zwick-1474 machine at a constant cross-speed of 1 mm/min, at room temperature. An appropriate fixture was used for flexural tests. Figure 7.5 shows the test set up for flexural bending strength. Following equation (eq. 7.3) was used for the calculating the flexural strength:

$$FS = \sigma = \frac{3 \times P_R \times l}{2 \times t_s^2 \times w_s} \qquad \text{(eq. 7.3)}$$

where:

FS = flexural strength (MPa),

P_R = rupture load (N),

l = support span (mm),

w_s = width of specimen (mm),

t_s = thickness of specimen (mm).

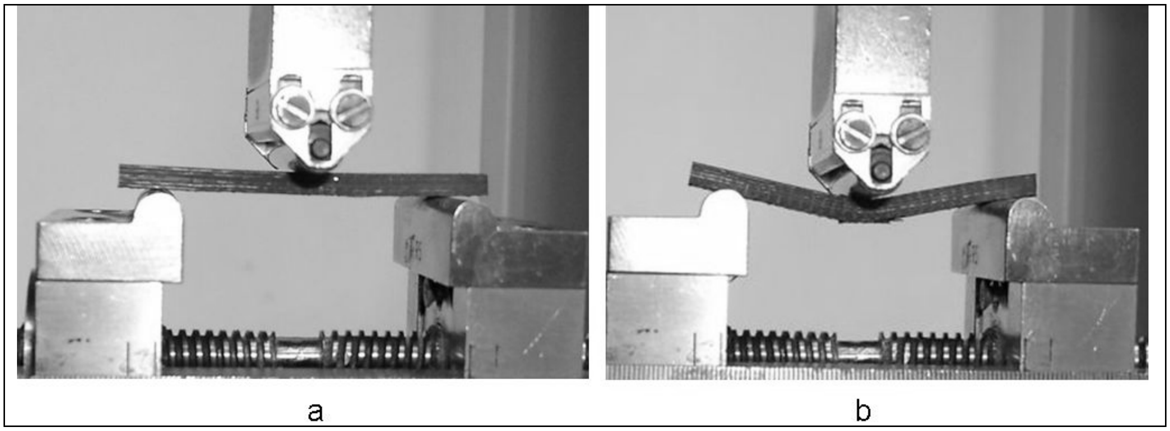

Figure 7.5: Test set-up for flexural bending: a) position before bending, b) position after bending

Microscopic analyses

Microscopic observations of stitch geometry (transverse and in-plane) were performed to investigate impregnation level of the sewing thread, stitch geometry, and seam quality. After the mechanical tests, fractured specimens of each laminate family were analyzed by stereo microscopy to identify the failure mode occurrence. Figure 7.6 shows micrographs of stitch geometry of stitched laminates using carbon threads. It can be observed from figure that the carbon threads including polyester wraps are well impregnated and stitch quality in terms of ellipses with matrix rich regions has been improved.

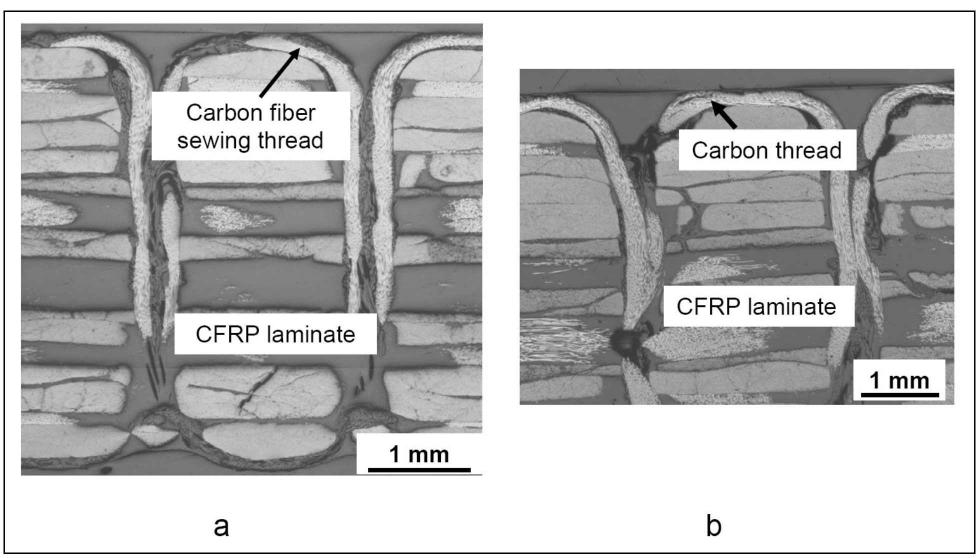

Figure 7.6: Seam appearance inside the laminate a) CF-1; b) CF-2

7.2.2 Results and discussion

Interlaminar shear strength

According to Table 7.1 shear strength values of the unstitched laminates (τ(u)) and sewn laminates (τ) are different which is again depends on the fiber direction and type of sewing thread used. These results indicate that the carbon fabric sewing affects the shear properties of the laminate.

A significant influence of the thread material on the interlaminar shear strength can be observed in the stitched laminates. In this case, it is also illustrated that the laminates stitched with PBO shows much improvement causing higher ILSS values than the other laminates. In general, ILSS has improved approximately 10-25 % in 0° to sewing direction (τ_0) and approximately 5-15 % in 90° direction (τ_{90}).

Figure 7.7 shows the bending stress-strain curve for short beam test specimens. The unstitched specimen shows only three failure peaks, however, the stitched specimens show peak for load at rupture and number of peaks in between the load at rupture and final failure load.

Table 7.1: Summary of ILS strength

Composite	ILSS			
	τ_0 [MPa]	$\tau_0/\tau^{(u)}_0$ [%]	τ_{90} [MPa]	$\tau_{90}/\tau^{(u)}_{90}$ [%]
Unstitched*	45.0 ± 1.5	100	27.0 ± 1.1	100
Stitched with CF-1	49.51 ± 1.3	110.0	28.42 ± 0.9	105.4
Stitched with CF-2	50.49 ± 2.1	112.1	30.35 ± 0.8	112.5
Stitched with PBO	55.47 ± 1.9	123.2	29.21 ± 1.2	108.3

* $\tau = \tau^{(u)}$

It is observed from Figure 7.7 that the sewn laminates are relatively less stiff than the unsewn laminates. Furthermore, the specimen stitched with PBO thread shows higher peak but it is much stiffer than the other sewn laminates. Specimen stitched with carbon threads shows relatively low stress values but high strain values. In-plane modulus of sewn laminate is much less than the sewn laminate. This supports the literature findings.

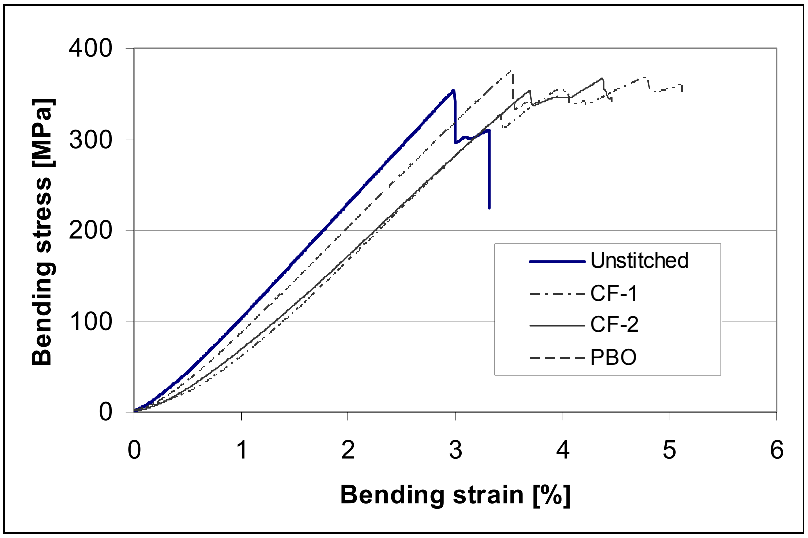

Figure 7.7: Typical stress strain curves (short beam test)

It is also observed that fiber distortion, fiber breakage, and overall laminate quality certainly influence the laminate properties. However, the overall enhancement of shear properties shows that TTT sewing overcomes the reduced through-the-thickness properties due to sewing imperfections.

In 90° test direction, specimens stitched with CF-2 show relatively increased ILSS values because this thread made lower reinforcing fiber deformation. Figure 7.8 shows micrographs of in-plane laminate indicating elliptical fiber deformation. If higher fiber deformation occurs, it causes resin filled pockets in thickness direction of laminate, which clearly weakens the yield strength.

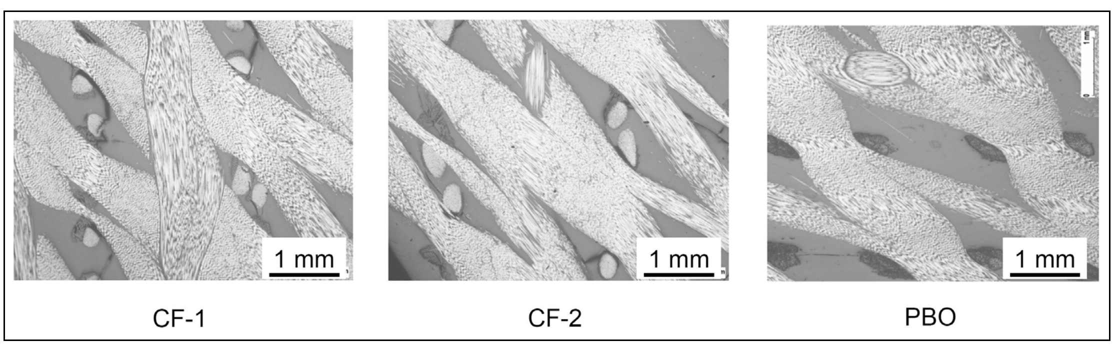

Figure 7.8: Reinforcing fiber-spread caused due to different sewing threads

Previous work on similar type of studies shows that as far as interlaminar shear is concerned, it is usually improves with sewing [55, 116], but in some cases it degrade [117] or does not affect. The literature also reports that with increase in stitch density, interlaminar shear strength also increases. The range of degradation or enhancement in the properties is 15-20 % (based on the maximum stitch density: 12 stitches/cm^2). In this study, a stitch density of 16 stitches/cm^2 enhance shear properties both in 0° and 90° direction of sewing.

Flexural bending test

Table 7.2 illustrates flexural strength values of all tested laminates (0° to sewing direction: σ_0, and 90° to sewing direction: σ_{90}) and changes with reference to unstitched laminate ($\sigma_0/\sigma^{(u)}_0$ and $\sigma_{90}/\sigma^{(u)}_{90}$). Considering the standard deviation, it can be realized that the flexural strength values of the stitched laminates are very close to one another. However, it can also be observed that unstitched laminate strength is higher in case of 0° stitched laminates. In case of 90° to the sewing direction, the bending strength is increased by up 11 %.

A typical stress-strain diagram for different specimens is shown in Figure 7.9. The progressive fracture in case of sewn laminates is clearly visible. Here, it has been clearly illustrated that the flexural bending strength and in-plane modulus of unstitched laminate is higher than the stitched ones.

Table 7.2: Summary of flexural bending test

Composite	Flexural bending strength					
	Testing 0° to stitching direction			Testing 90° to stitching direction		
	σ_0 [MPa]	$\sigma_0/\sigma^{(u)}_0$ [%]	E_0 [GPa]	σ_{90} [MPa]	$\sigma_{90}/\sigma^{(u)}_{90}$ [%]	E_{90} [GPa]
Unstitched#	685.90 ± 19.6	100	46.88	222.98 ± 17.9	100	23.39
Stitched with CF-1	524.28 ± 23.1	76.4	37.73	223.88 ± 18.5	100.4	18.58
Stitched with CF-2	529.88 ± 25.2	77.2	38.40	239.92 ± 17.3	107.6	18.18
Stitched with PBO	553.93 ± 31.4	80.7	40.51	247.38 ± 20.2	110.9	18.40

$\sigma = \sigma^{(u)}$

The distorted crack growth in sewn laminate is visible in Figure 7.10. As explained in earlier sections, the matrix rich areas form in the laminate due to fiber distortion during sewing; this area is prone to crack after the application of loads. Figure 7.11 shows micrograph of failed specimen (cracking of matrix filled zone).

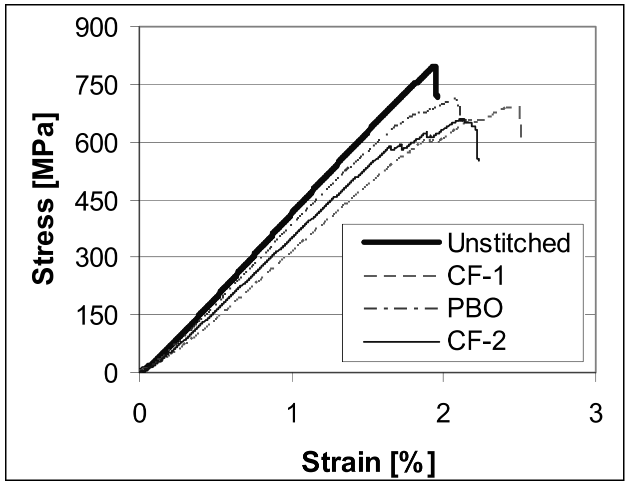

Figure 7.9: Typical stress-strain diagram (flexural bending test)

Mouritz et al. [55] studied the effect of stitching density on flexural properties of the laminates. The author observed that sewing usually degrades or has no significant effect on flexural strength. However, other similar type of studies shows that the flexural strengths of laminate improved substantially by sewing [116, 117]. Furthermore, it has also been reported that with increase in stitch density flexural strength decreases.

However, the reported literature has not discussed about flexural strength in parallel to sewing and perpendicular to sewing direction. Therefore, in present study the experiments were performed to support all the literature findings with apparent view on testing-direction dependant results. In inter laminar shear strength testing, specimens tested in parallel to sewing direction shows significant increase in the strength values. Whereas, specimens tested perpendicular to sewing direction shows relatively lower effect on ILSS. In flexural bending results, specimens parallel to sewing direction shows decrease in strength and specimens perpendicular to sewing direction illustrate negligible to notable increase in strength.

Microscopic observations of failed specimens

As shown in Figure 7.10 and Figure 7.11, the cracks can not be seen bridging across the stitch; this shows that the interlaminar region has not completely failed in this zone. In stitched material the stiffness is lower therefore the laminate properties emerge partly from the Z-directional fibers. It also means that the TTT threads prevent the crack growth and propagation in various laminate layers. This can be realized from the crack growth in the micrographs.

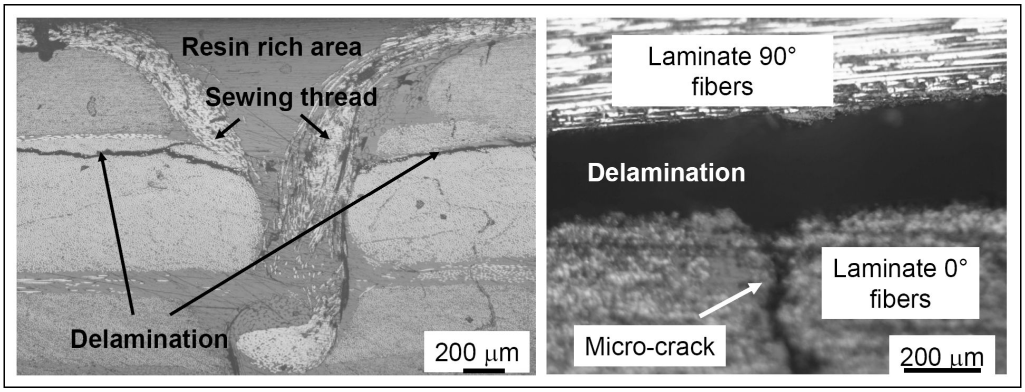

Figure 7.10: Micrographs of fractured laminates

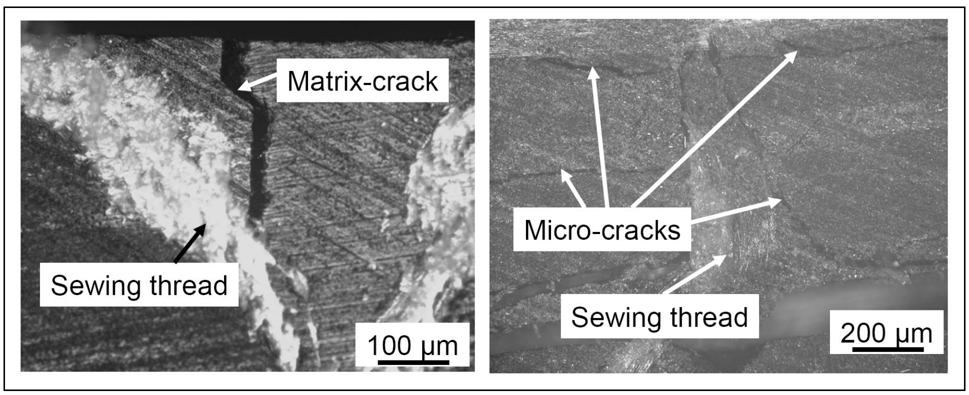

Figure 7.11: Matrix cracking and failure around sewing thread

As far as the matrix micro-crack is concerned, in stitched laminate, cross-ply cracks are present throughout the width over the all resin rich regions. However, in case of unstitched laminate, matrix-cracks are not present even at the high matrix rich zones. Figure 7.12 shows micrographs of stitched and unstitched laminates. The reason behind this phenomenon might be the stitches that do not allow delamination at the initial load application; as a result, the matrix rich zones carry the entire load and generate a crack. Reinforcing fibers carry the additionally exerted loads which causes ply delamination. Whereas in unstitched laminates, delamination occurs relatively quicker, without transferring initial load to matrix rich zones and as the loading progresses, now the weak region is delaminated plies, thus, there is no possibility to transfer additional load on resin rich areas.

Delamination of plies due to compression (shear failure of laminate subjected to transverse compressive load due to bending) is a very typical phenomenon and the layers fractured due to compression were observed in both stitched and unstitched laminates (Figure 7.13). Though, stitches involved in the stitched laminate hinder mechanical fracture, the laminate zones where stitches do not have any influence are observed for compression fracture.

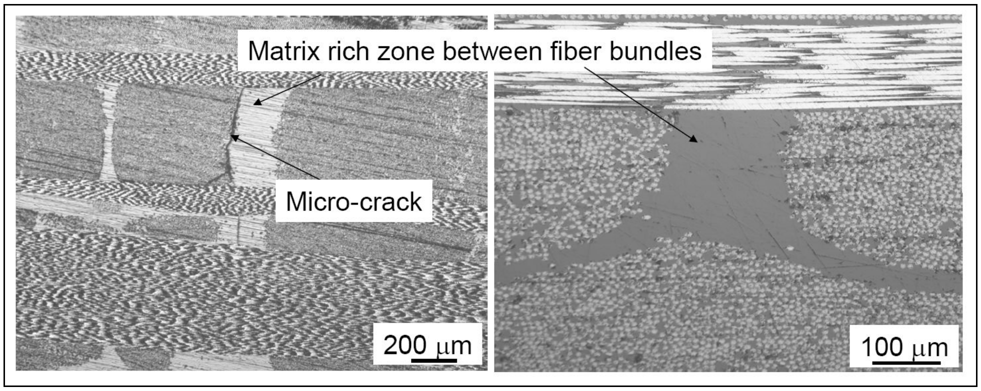

Figure 7.12: Resin rich areas in stitched and unstitched laminate (possibilities of micro-crack)

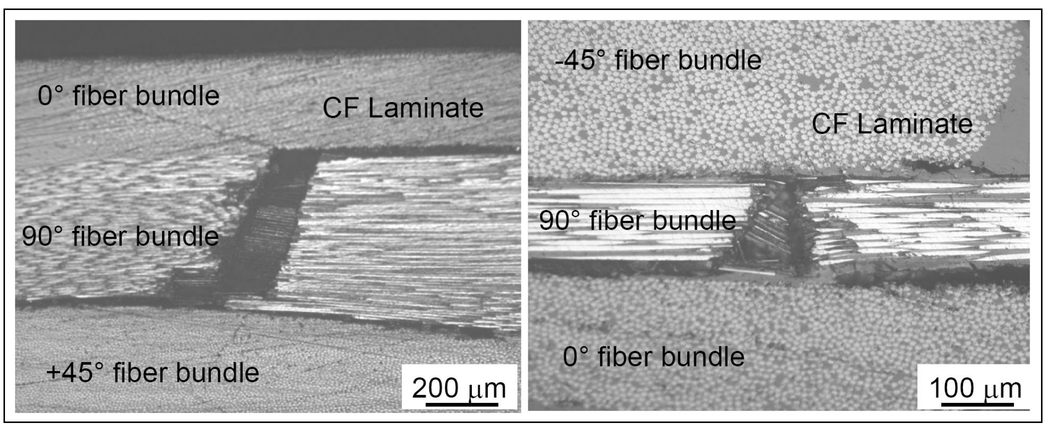

Figure 7.13: Typical laminate fracture due to compression

Failure behavior of laminate is shown in Figure 7.14. Here, though the testing procedure was not aimed to establish failure modes, according to literature and micrographs obtained from scanning electron microscope (SEM) analysis, it can be stated that the majority of specimens fail in Mode-II form. It has also been observed that due to proper fiber matrix bonding, intra ply laminate failure is the major mode of delamination.

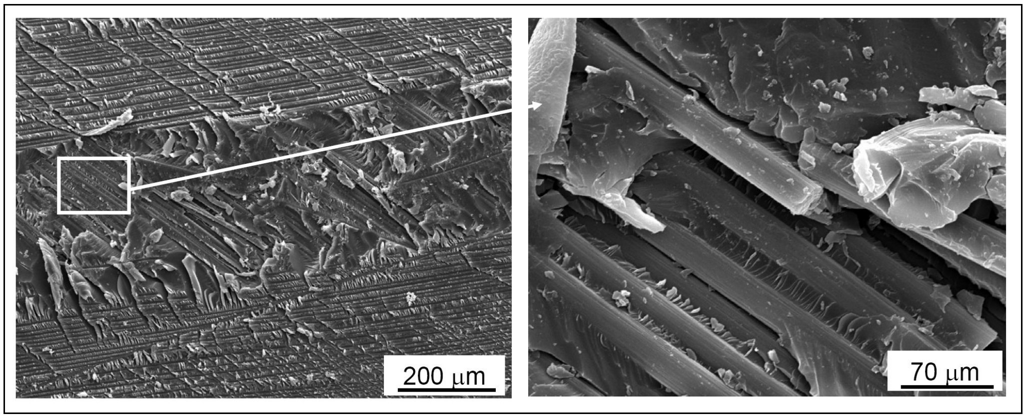

Figure 7.14: SEM micrograph of failed unstitched laminate surface showing mode of failure

7.3 Summary

Sewing increases the interlaminar shear properties by ~10-25 % in 0° to the sewing direction and by ~5-15 % in 90° to the sewing direction. Sewing degrades flexural bending strength (up to 25 %) in 0° to the sewing direction because of damage and fiber distortion caused during sewing. But because of formation of roving bundles and compaction the strength enhance in 90° to the sewing direction (up to 11 %). Stitches arrests the crack propagation and avoids major delamination but as an effect, all the matrix rich zones prone to the micro-cracks. Whereas in unstitched laminates, matrix micro-cracking was not present but only the major delamination along the specimen length has occurred. Among the three different threads, the PBO thread is more suitable for high speed sewing operation and the properties obtained from the stitched laminated are much superior than the carbon fiber threads.

8 Quality aspects of net-shape preforms

The process of sewing, on the one hand improves the handling of dry structure, efficiency of LCM processing, and interlaminar properties. On the other hand, as discussed in the Chapter 2 and 3, stitches create disorientation of the reinforcing material, discontinuity of the aligned tows or roving, and fiber damage at localized zone. Apart from that, changes in localized fiber volume fraction and preform permeability have to be qualified.

As far as quality aspects of the FRPC laminate are concerned, apart from sewing thread properties; machine modifications, sewing parameters, and finally the preform assembly practices are the dominating factors. The actual behavior of sewing thread inside the preform and later in the FRPC laminate with reference to sewing parameters are found to be interesting for the study.

The current chapter explains the influence of preform compaction on preform quality aspects including fabric deformation phenomenon. Influence of sewing sequence on warpage and influence thread parameters on change in area weight and absolute reinforcing fiber volume content is also examined. Net-shape preform cutting is a key issue for mold placement, thus, possibilities of accurate cut is also explained at the end of the chapter.

8.1 Influence of preform compaction on preform quality aspects

As discussed in introductory chapter, sewing or sewing routines are highly flexible production methods for assembling complex dry fiber preforms. Furthermore, textile assembling is advantageous in terms of ready to dispatch products with reduced cycle time and cost [118, 119]. Thus, assembling of textile reinforcements to net-shape geometry is a functional aspect of preform sewing. Parallel to the routine and the preforming aspects, it is also observed that, the stitch formation phenomenon is governed by various factors like: thread tension, compaction during sewing, needle system, and material feeding action. Weimer et al. described the sewing process parameters influencing on the properties of the FRPC laminates. Preform compaction in the mold is very critical factor because reinforcing material has to be compressed to achieve required final thickness of the product. If the preform is too thin, skin-tracking appears, which leads to the defective surfaces. However, net-shape preforms are almost impossible to realize applying non compacted preform packages. A partial compaction possibility is a prerequisite in order to achieve proper tool loading and net-shape potential. On the other hand, preforms should be flexible enough where it is desired.

8.1.1 Fabric deformation

Textile woven fabrics consist of wavy warp and weft elements. On the application of perpendicular force, the crimp in the warp and weft keeps reducing to the jamming condition [100]. As the crimp reduces, the effective fabric dimensions increases, it means fabric deforms to certain extent. Figure 8.1a shows schematics of possible free deformation of a woven fabric. If fabric boundaries are fixed partially or completely, the lateral deformation of the textile fabric will be restricted and jamming condition occurs much earlier. Figure 8.1b to Figure 8.1d shows possibilities of boundary blocking. In the same fashion, stitches can work as a definite boundary and the amount textile fabric comes under these boundaries can differs according to the stitch pattern. Figure 8.1e shows schematics of unstitched lay-up and boundaries formed due to stitches.

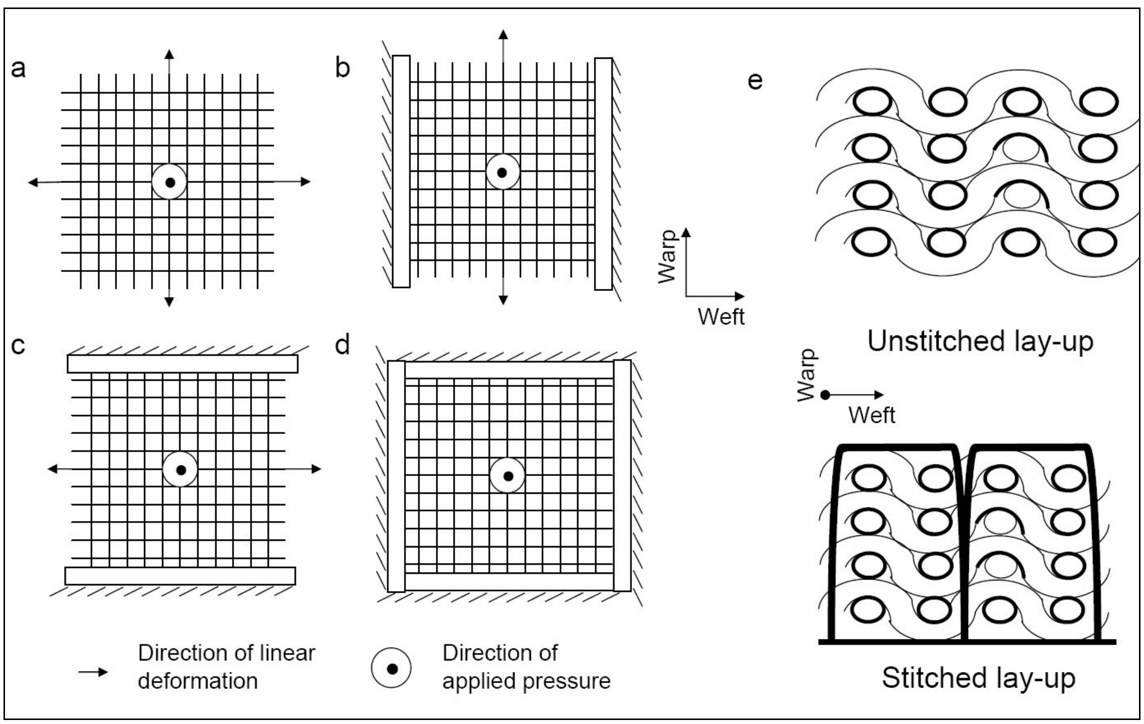

Figure 8.1: Phases of deformation

Due to applied thread tension and elastic behavior of sewing thread warp and weft rovings falls under the seam line have a tendency to densify. Figure 8.2 shows schematic diagram of fabric orientation at the stitched section. This effect is directly proportional to the thread tension and inversely proportional to the thread elasticity. Due to the densification of rovings a bulge formation may occur.

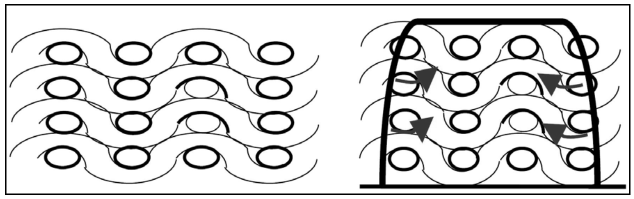

Figure 8.2: Packing of rovings at the stitch section

Figure 8.3 suggest the same phenomenon but here it is clearly observable that, low stitch density reduces the overall weight of preform, whereas high stitch density increases the effective weight of preform. Furthermore, preform fiber volume faction immediately after the stitching is affected by the change in preform weight due to sewing. As shown in Figure 8.4, due to precompaction after stitching, preforms stitched with high stitch density (13.33 stitches /cm^2) shows relatively higher fiber volume at minute compaction pressure than the preforms stitched with medium (6.67 stitches /cm^2) or low stitch density (3.33 stitches /cm^2).

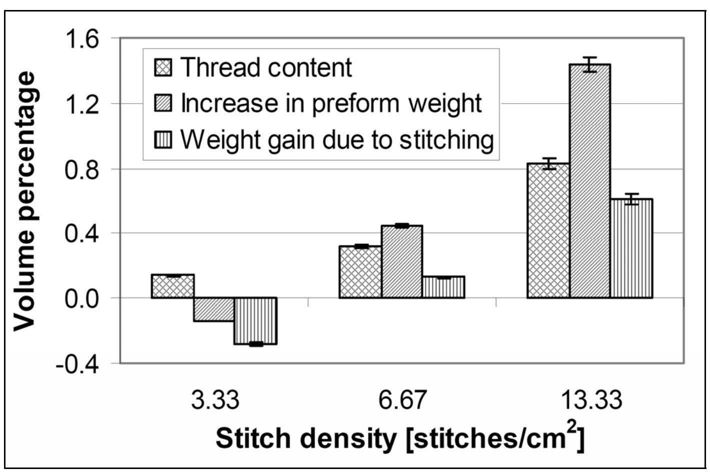

Figure 8.3: Change in preform area weight according to stitch density.

The stitched boundaries blocks the fabric deformation during the later stages of tool loading, however, the process of sewing itself deforms the textile fabric to certain extent. When the needle penetrates through the material and forms a stitch, the thread is under tension which exerts pressure on the fabric lay-up which reduces the fabric crimp at localized section. This deformation is only in perpendicular to the sewing direction. After the first sewing row when machine place the adjacent rows of stitches, a localized zone of fabric, in between the two rows, forms a bulge like geometry. Figure 8.5 shows two different cases of bulge formation. In uni-directional sewing, the intensity of bulge formation is lesser than the bi-directional sewing (square).

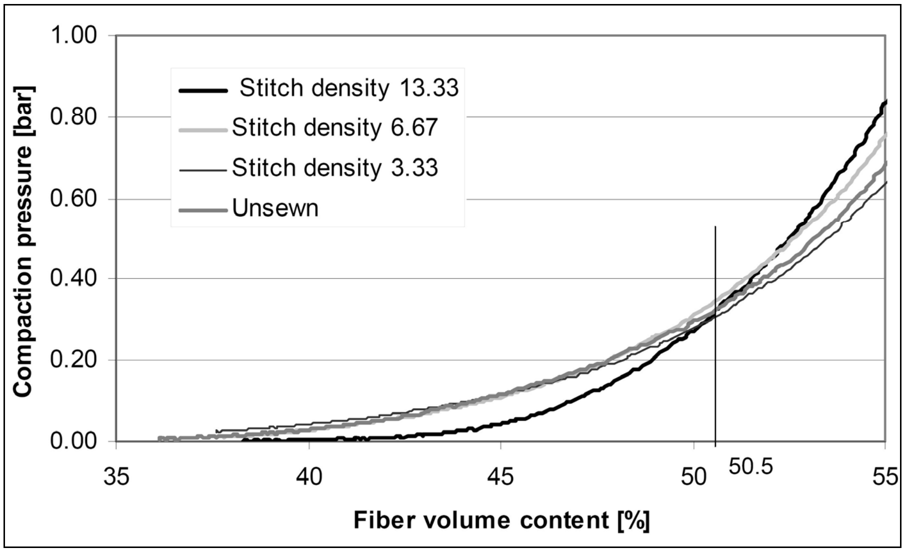

Figure 8.4: Change in preform weight corresponds to initial fiber volume content, sewing thread used: textured thread, thread tension: high, fabric used: woven 2/2 twill

The bulge formation is not only depends on the direction of sewing but also on the sewing pattern and stitch density. Figure 8.6 shows two different sewing patterns and corresponding schematic views explaining the compaction at stitch (C) and bulge (B1 and B2). Here, because of compact stitches, bulge B1 is greater than bulge B2. From the experiments performed for the preform compaction, it has also been observed that the stitch density is directly proportional to the bulge formation. It means with higher stitch density the boundaries for blocking of the fabric material are also more.

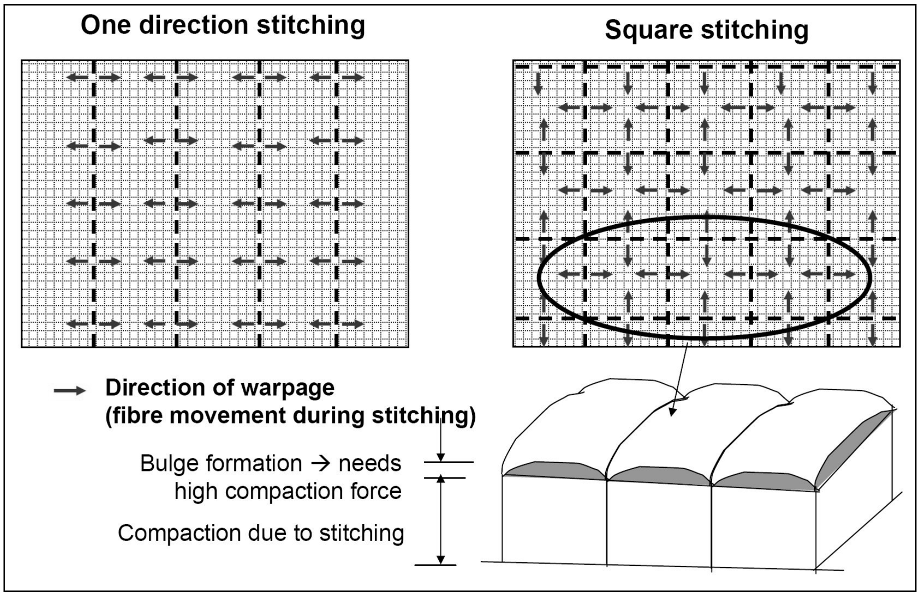

Figure 8.5: Warpage at uni-directional and bi-directional sewing

Low stitch density allows deforming of the preform to a small extent. This reduces the further chances of fluid matrix race-tracking. Whereas, high stitch density does not allow any deformation, which characterizes it for the net-shape preform with pre-defined fiber volume. Consequently the total fabric deformation due to sewing is negligible. Furthermore, the formed bulge takes the complete tooling load during the RTM mold closure, which helps to retain the net-shape geometry of the preform. Apart from this, as explained in the earlier section, the phenomenon of bulge compaction may reduce the size of stitch-hole, hence improves the preform quality.

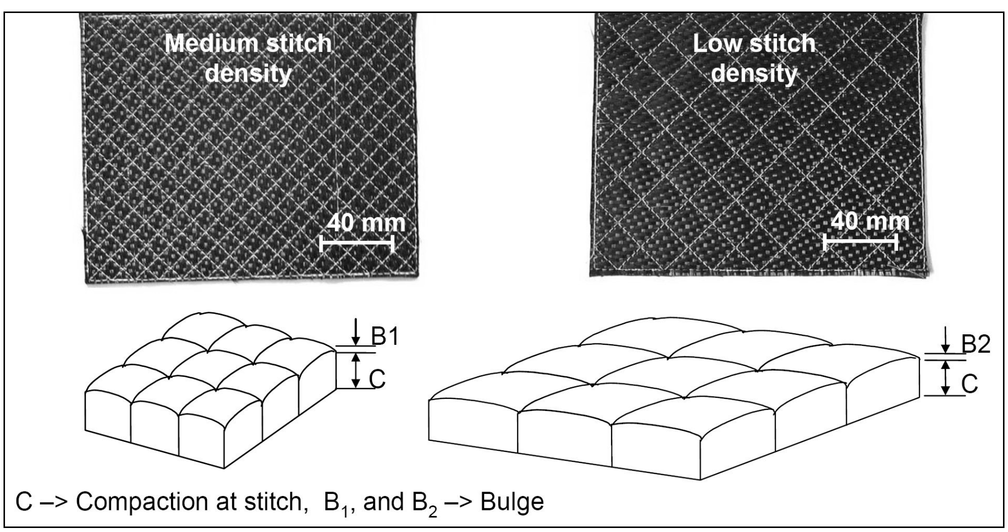

Figure 8.6: Sewing pattern as a function of preform compaction and quality

8.2 Influence of sewing sequence

As explained in the previous section of fabric deformation, the textile fabric tends to deform due to sewing. During the generation of sewn pattern, as the number of sewing rows progresses, the deformation of fabric transfers from first row to the last row. At the end, the cumulative deformation comes to an effect. Therefore the sewing sequence is very important factors as far as the generation of preforming seam is concern.

Figure 8.7 shows accumulation of deformation or warpage as a function of sewing direction. If the sewing sequence is -45° and then +45° rows then the accumulation of warpage will be exactly at the opposite direction of the starting point of sewing. It is the same case for 0/90 degree sewing.

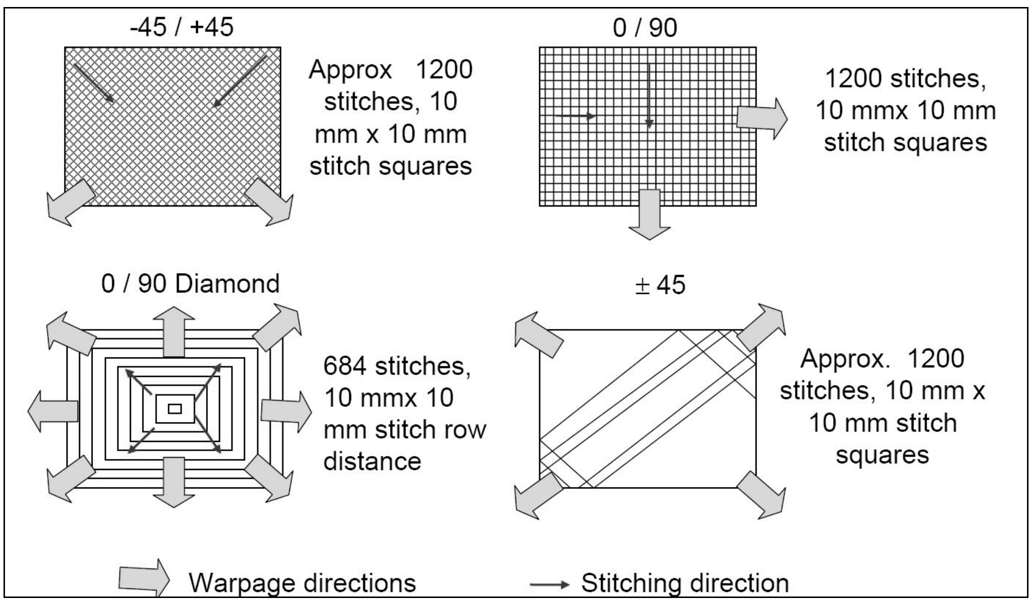

Figure 8.7: Influence of sewing sequence on warpage

To achieve well distributed warpage, a diamond type of sewing sequence can be followed. But in this case the preform won't be stable enough to handle and this sequence causes maximum warpage, which reduces the effective preform area weight. To avoid this shortcoming, a random sewing sequence in ±45° direction (alternate -45°/+45° from inner most to outer most preform boundaries) can be applied. In this approach the stitch density will be maintained and fabric deformation can be distributed in all the directions, thus, there will be no compromises in the preform handling characteristics.

8.3 Influence of thread on reinforcing fiber volume content

Thread content in the preform is depend on preform length (l_p), width (w_p), and thickness (tp), various sewing pattern parameters, such as, stitch length (l_{st}), stitch row width (w_{st}), and finally the thread linear density, tex (ρ_l). From these parameters amount of thread content in terms of weight percent and volume percent in the complete preform can be calculated. Thread content in grams can be calculated as:

$$W_t = \frac{(\rho_l \times 2 \times l_p \times w_p \times l_p \div w_{st}) \times (1 + (2 \times \rho_t \div l_{st}))}{1000} \quad \text{(eq. 8.1)}$$

From thread weight and density of thread material (ρ_t), thread volume (V_t) all over the preform can be calculated:

$$V_t = \frac{W_t}{\rho_t} \quad \text{(eq. 8.2)}$$

Therefore,

$$\textit{Sewing thread volume fraction} = \frac{V_t}{V_l} \quad \text{(eq. 8.3)}$$

Where V_l is total laminate volume which is summation of reinforcing fiber volume (V_f) and matrix volume (V_m).

At the stitch-hole area the amount of base reinforcing fiber is negligible; rather the sewing thread fills this area, thus, at this section,

$$V_l = V_t + V_m \quad \text{(eq. 8.1)}$$

Furthermore, V_m is depending on number of parameters, for instance, sewing thread tension, needle type and size, and thread geometry.

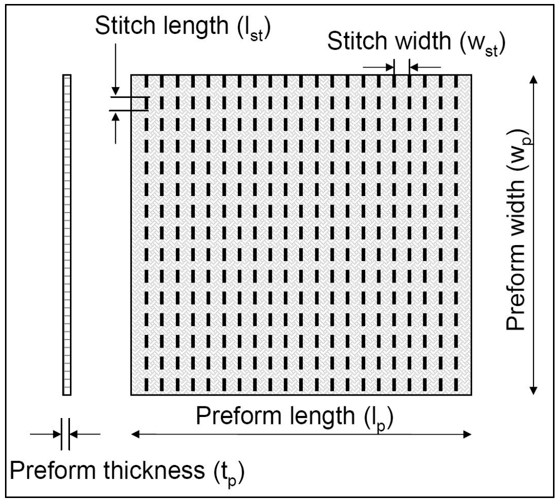

Figure 8.8: Schematic diagram of preform parameters

In case of preforming seam, polyester thread volume generally falls between 0.5 % and 2 % depends on the stitch density (stitches/cm^2). By using above mentioned formulae it is possible to choose a desired sewing pattern for particular amount of sewing thread in the final FRPC.

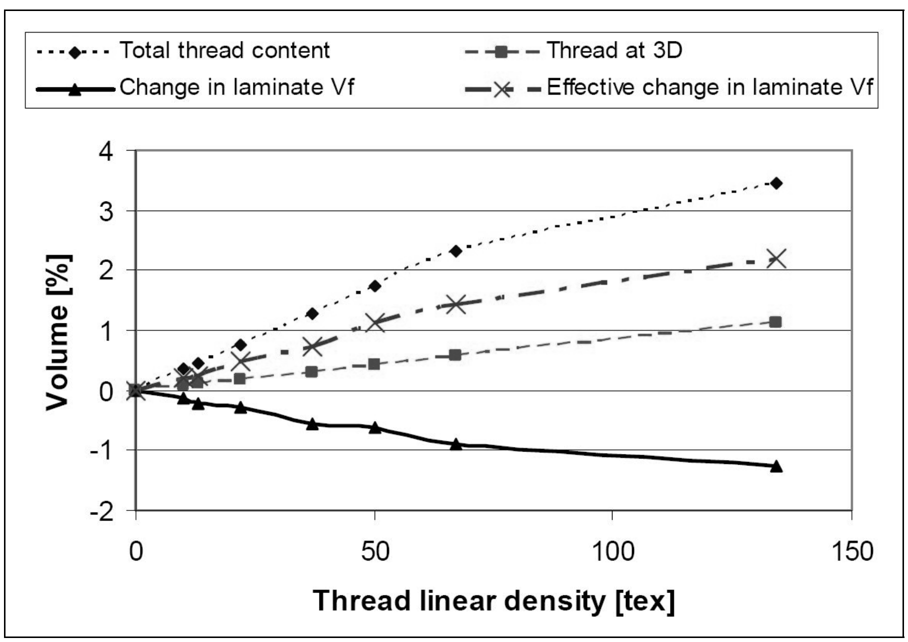

Figure 8.9: Sewing thread content and change in reinforcing fiber volume

Due to the sewing process and involved thread in the preform geometry reinforcing fiber volume content in the final laminate may affect considerably. Figure 8.9 shows change in reinforcing fiber volume as a function of thread linear density (tex). After sewing, due to warpage of the textile material the amount of reinforcing fiber reduces to some extent but textile fiber content in the laminate increases because of the sewing thread involved. This increase in fiber volume is considerable in uni-fiber preform, e.g., CF fabric stitched with the CF thread.

8.4 Influence of sewing on preform permeability and impregnation

During the sewing cycle, needle with the sewing thread penetrates through the fabric lay-up forms a stitch and comes up to form next stitch. This phenomenon with the effect of applied thread tension causes fiber misplacement which introduces porous zones. Caused porosity is dependent of stitch density, thread diameter, and needle diameter. Figure 8.10 explains influence of thread tension of increase in porosity and caused effect on resin flow front along the stitched row. Due to this increase in porosity, highly compacted preforms can also gets impregnated without much difficulties during the RTM processing. In literature as well it has been well studied that stitch density is directly proportional to permeability of preform.

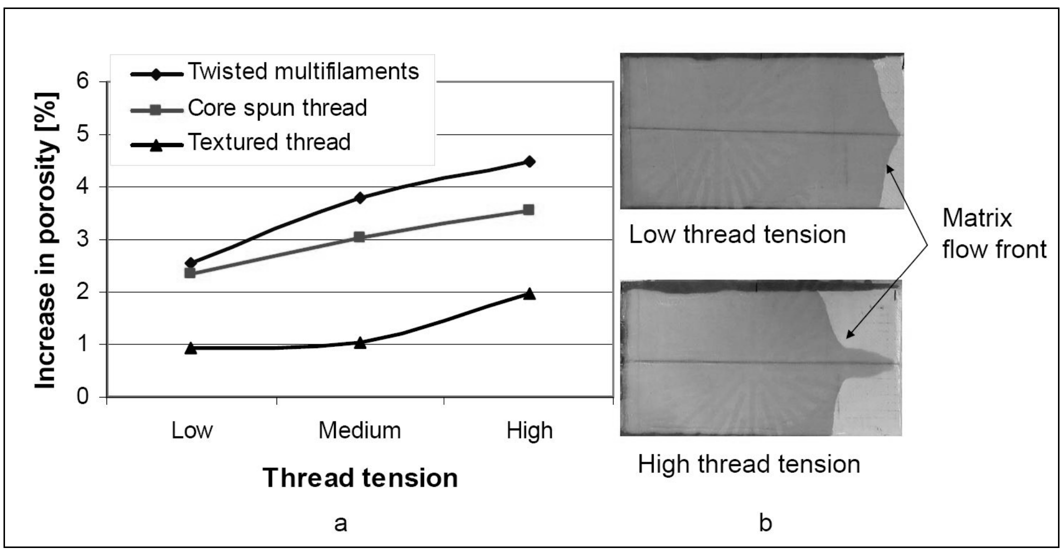

Figure 8.10: a) Influence of thread tension on preform porosity and b) matrix flow front at stitch line as a function of thread tension [120]

The reason behind the fast resin flow front is change in preform permeability after sewing. At the local section, preform permeability is either much higher (due to needle penetrations) or much lower (due to warpage, bulged preforms and accumulation of fibers). Figure 8.11 shows influence of stitch density on increase in preform porosity and hence preform permeability.

Han et al. [121] investigated the influence of sewing on resin film infusion process. The result shows that the sewing enhances the through-the-thickness permeability of fabric preform, thereby reducing the minimum pressure required for full resin infiltration. Furthermore, the infiltration time is predicted to reduce by 7 %.

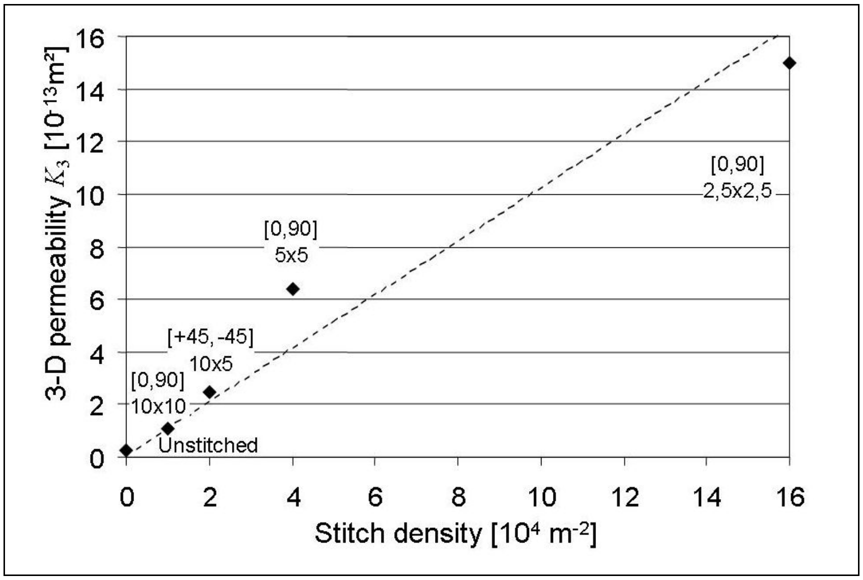

Figure 8.11: Influence of stitch density of preform permeability [100]

8.5 Summary

Different sewing parameters: stitch density, stitch pattern, and various stitch formation particulars define the characteristics of a sewn preform. The compaction behavior of a stitched fabric stack dominates deformation of a preform and consequently determines mold placement approach. The lay-up of the textile, in context of the sewing direction itself is found to be influencing factor on the whole compaction process and warpage. Preform sewing sequence is also helpful for net-shape preform manufacturing. In terms of preform quality, all these parameters need to be adjusted according to the specifications of FRPC components.

9 Conclusions

In the present study, the sewing aspects responsible for the net-shape preforming, preform quality parameters, role of preform in LCM processing, and laminate behavior are thoroughly investigated.

Various important properties essential for a sewing thread to be used for preforming are discussed in detail. Types of sewing threads available for preforming and their pros and cons are summarized which can help to select a proper thread for particular preform manufacturing.

Preform quality in terms of fiber-spread, ellipse formation, missing stitch, etc. and defects formed due to these imperfections are explained in detail. Reduction in preform flaws can improve laminate structure and optics. The use of statistical tool helped to investigate the effect of individual factor and combination of multiple factors on preform defects. Sewing threads with improved geometrical characteristics, special threads made up of epoxy soluble or quick melting polymers, RTM tooling process, and liquid matrix injection process help to reduce ellipse size and improve laminate quality. Apart from this, process compatible sewing thread sizing can reduce degassing, bubble formation, and void formation phenomenon.

Different sewing parameters, such as stitch density, stitch pattern, and various stitch formation particulars define the compaction of the fiber package. The compaction behavior of a stitched fabric stack is dominated by fabric architecture. The sewing parameters have to be selected according to the thread used, lay-up of the reinforcing structures, and the type of reinforcing fabric. It can be stated that the combination of high thread tension and higher stitch density or low thread tension and low stitch density have advantage over the unsewn preform. Linear and non-linear compaction is a function of fiber volume and fiber packing during the compaction phenomenon. Phases of preform compaction illustrate the force needed to achieve a final fiber volume fraction.

Various polyester sewing threads are analyzed for their usability in preforming and joining seam. Sewing thread design and geometry had significant effect on the quality of preform, FRPC processing, microstructure, and properties of the laminates. Impregnation of a sewing thread is a key factor for improving the mechanical and thermal properties of FRPC. The study of sewing thread material and the sizing is concludes that the textured single threads are the most suitable sewing elements to improve mechanical characteristics of stitched laminates. However, it can be recommended that these threads have to be structurally improved for its utilization at high speed sewing stations.

A study on high performance sewing threads illustrates that the interlaminar shear properties and flexural bending strength are dependent on loading direction. The microscopic observations conclude that in unstitched laminates, matrix micro-cracking and the major delamination along the specimen length are the outcome of mechanical loading. In Stitched laminates, stitches arrests the crack propagation and avoids major delamination, however, as an effect, all the matrix rich zones prone to micro-cracks. Among the three different types of threads, PBO threads are more suitable for high speed sewing operation and the properties obtained from the stitched laminated are much superior than the carbon fiber threads.

Influences of preform manufacturing process on the preform quality are well documented. Applied thread tension causes reduction in fabric crimp and shifting of fibers. This phenomenon influence the absolute weight of the reinforcing fibers but the applied sewing thread remains inside the preform, thus, the overall fiber volume content becomes unchanged or increases slightly. The increase in high performance fiber volume is depends on the high performance thread linear density.

The studies discussed in this thesis can help to develop the preforms with improved quality which can enhance composite laminate characteristics and mechanical performance. Preform manufacturing practices and RTM procedures can be improved by selecting appropriate preforming and tool loading parameters. Good quality preforms and composite components can reduce rejections and wastage. Thus, further exploitation of sewing technology for superior composite components is well achievable.

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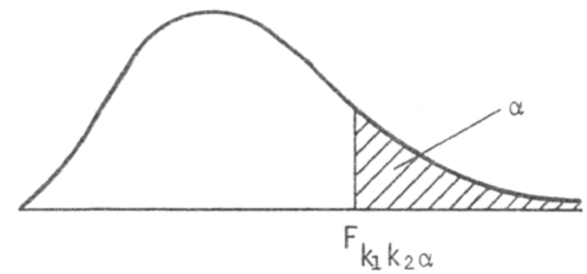
Apendix A1: F table

Table A1: Probability points of the F distribution
The entrieds in this table are the values of $F_{k_1 k_2 \alpha}$ corresponding to the given value of α
$\alpha = 0.05$



k_2	k_1 = 1	2	3	4	5	6	7	8	9	10	20	∞
1	161	200	216	225	230	234	237	239	241	242	248	254
2	18.5	19.0	19.2	19.3	19.3	19.3	19.4	19.4	19.4	19.4	19.5	19.5
3	10.1	9.6	9.3	9.1	9.0	8.9	8.9	8.9	8.8	8.8	8.7	8.5
4	7.7	6.9	6.6	6.4	6.3	6.2	6.1	6.0	6.0	6.0	5.8	5.6
5	6.6	5.8	5.4	5.2	5.1	5.0	4.9	4.8	4.8	4.7	4.6	4.4
6	6.0	5.1	4.8	4.5	4.4	4.3	4.2	4.2	4.1	4.1	3.9	3.7
7	5.6	4.7	4.4	4.1	4.0	3.9	3.8	3.7	3.7	3.6	3.4	3.2
8	5.3	4.5	4.1	3.8	3.7	3.6	3.5	3.4	3.4	3.4	3.2	2.9
9	5.1	4.3	3.9	3.6	3.5	3.4	3.3	3.2	3.2	3.1	2.9	2.7
10	5.0	4.1	3.7	3.5	3.3	3.2	3.1	3.1	3.0	3.0	2.8	2.5
15	4.5	3.7	3.3	3.1	2.9	2.8	2.7	2.6	2.6	2.5	2.3	2.1
20	4.4	3.5	3.1	2.9	2.7	2.6	2.5	2.5	2.4	2.4	2.1	1.8
∞	3.8	3.0	2.6	2.4	2.2	2.1	2.0	1.9	1.9	1.8	1.6	1.0

Table A1 (continued)
$\alpha = 0.025$

k_2	k_1 = 1	2	3	4	5	6	7	8	9	10	20	∞
1	648	800	864	900	922	937	948	957	963	969	993	1018
2	38.5	39.0	39.2	39.3	39.3	39.3	39.4	39.4	39.4	39.4	39.5	39.5
3	17.4	16.0	15.4	15.1	14.9	14.7	14.6	14.5	14.5	14.4	14.2	13.9
4	12.2	10.7	10.0	9.6	9.4	9.2	9.1	9.0	8.9	8.8	8.6	8.3
5	10.0	8.4	7.8	7.4	7.2	7.0	6.9	6.8	6.7	6.6	6.3	6.0
6	8.8	7.3	6.6	6.2	6.0	5.8	5.7	5.6	5.5	5.5	5.2	4.9
7	8.1	6.5	5.9	5.5	5.3	5.1	5.0	4.9	4.8	4.8	4.5	4.1
8	7.6	6.1	5.4	5.1	4.8	4.7	4.5	4.4	4.4	4.3	4.0	3.7
9	7.2	5.7	5.1	4.7	4.5	4.3	4.2	4.1	4.0	4.0	3.7	3.3
10	6.9	5.5	4.8	4.5	4.2	4.1	4.0	3.9	3.8	3.7	3.4	3.1
15	6.2	4.8	4.2	3.8	3.6	3.4	3.3	3.2	3.1	3.1	2.8	2.4
20	5.9	4.5	3.9	3.5	3.3	3.1	3.0	2.9	2.8	2.8	2.5	2.1
∞	5.0	3.7	3.1	2.8	2.6	2.4	2.3	2.2	2.1	2.1	1.7	1.0

Table A1 (continued)
$\alpha = 0.01$

k_2	k_1 = 1	2	3	4	5	6	7	8	9	10	20	∞
1	4052	5000	5403	5625	5764	5859	5928	5982	6022	6056	6209	6366
2	98.5	99.0	99.2	99.3	99.3	99.3	99.4	99.4	99.4	99.4	99.5	99.5
3	34.1	30.8	29.5	28.7	28.2	27.9	27.7	27.5	27.4	27.2	26.7	26.1
4	21.2	18.0	16.7	16.0	15.5	15.2	15.0	14.8	14.7	14.6	14.0	13.5
5	16.3	13.3	12.1	11.4	11.0	10.7	10.5	10.3	10.2	10.1	9.6	9.0
6	13.8	10.9	9.8	9.2	8.8	8.5	8.3	8.1	8.0	7.9	7.4	6.9
7	12.3	9.6	8.5	7.9	7.5	7.2	7.0	6.8	6.7	6.6	6.2	5.7
8	11.3	8.7	7.6	7.0	6.6	6.4	6.2	6.0	5.9	5.8	5.4	4.9
9	10.6	8.0	7.0	6.4	6.1	5.8	5.6	5.5	5.4	5.3	4.8	4.3
10	10.0	7.6	6.6	6.0	5.6	5.4	5.2	5.1	4.9	4.9	4.4	3.9
15	8.7	6.4	5.4	4.9	4.6	4.3	4.1	4.0	3.9	3.8	3.4	2.9
20	8.1	5.9	4.9	4.4	4.1	3.9	3.7	3.6	3.5	3.4	2.9	2.4
∞	6.6	4.6	3.8	3.3	3.0	2.8	2.6	2.5	2.4	2.3	1.9	1.0

List of guided student's thesis

Stefanie Bold, 2003
Mechanische und thermoanalytische Charakterisierung von polyestervernähten Hochleistungs-Faser-Kunststoff-Verbunden.

Martina Trahan, 2004
Qualitative Analyse von genähten Preforms (trocken): Visuelle Online-Prüfung der Stichlochveränderung bei der Preformkompaktierung.