Process development for the manufacturing of flat knitted innovative 3D spacer fabrics for high performance composite applications

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Symbols and Abbreviations

Symbol	Designation
IPCC	The Intergovernmental Panel on Climate Change
G8	The Group of Eight
°C	Degree Celsius
CO_2	Carbon Dioxide
UD	Unidirectional
EU	The European Union
FRP	Fiber Reinforced Plastic
GF	Glass Fiber
PP	Polypropylene
2D	Two Dimensional
3D	Three Dimensional
CAD	Computer Aided Design
$\$US$	The United States Dollar
RTM	Resin Transfer Moulding
VI	Vacuum Infusion
SRIM	Structural Reaction Injection Moulding
Pa.s.	Pascal-Second
T_m	Melt Temperature
T_c	Crystallisation Temperature

Symbol	Designation
T_g	Glass Transation Temperature
CF	Carbon Fiber
PAN	Polyacrylonitrile
AF	Aramid Fiber
MPa	Mega Pascal
GPa	Giga Pascal
μm	Micro Metre
PEEK	Polyether Ether Ketone
PET	Polyethylene Terephthalate
PPS	Polyphenylene Sulfide
APS	Active Protection System
t_f	Thickness of Facing
h_c	Core Height
h	Sandwich Panel Height
I_f	Moment of Inertia
b	Breadth of Sandwich Panel
A	Vertical Area of the Unit Honeycomb Core
m	Mass of the Honeycomb Sandwich Panel
m_f	Mass of Facing Material
m_c	Mass of Core Material
ρ_{ca}	Average Density of Honeycomb Core
d	Breadth of Single Edge of Honeycomb Core Cell
t_c	Wall Thickness of Honeycomb Core Cell
ρ_c	Density of Honeycomb Core Material
t_{eq}	Equivalent Thickness
E_f	Elastic Modulus of Facing Material

Symbol	Designation
E_{eq}	Equivalent Elastic Modulus
G_f	Shear Modulus of Facing Skin
G	Core Shear Modulus
G_{eq}	Equivalent Shear Modulus
ρ_f	Density of Facing Material
σ_u	Ultimate Strength of Sandwich Panel in Axial Compression
σ_{fo}	Yield Stress of Facing Material
σ_f	Facing Bending Stress
τ_c	Core Shear Stress
P_1	Short Beam Load
P_2	Long Beam Load
c	Core Thickness
L_1	Short Beam Span Length
L_2	Long Beam Span Length
U	Panel Shear Rigidity
D	Panel Bending Stiffness
Δ	Total Beam Midspan Deflection
K	Knit Loops
T	Tuck Stitches
W	Weft Inlay
WA	Warp Inlay
WWA	Weft and Warp Inlays
T-K	Tube with Knit Loops
T-T	Tube with Tuck Stitches
T-W	Tube with Weft Inlay
T-WA	Tube with Warp Inlay

Symbol	Designation
T-WAT	Tube with Warp Inlay and Tuck Stitches
T-WWA	Tube with Warp and Weft Inlays
T-WWAT	Tube with Tuck Stitches including Warp and Weft Inlays
ITM	Institute of Textile Machinery and High Performance Material Technology
IFKM	Institute of Solid Mechanics
ILK	Institute of Lightweight Engineering and Plastic Technology
TU Dresden	Technische Universität Dresden
SFB 639	Collaborative Research Centre 639
T_{bk}	Tensile Strength before Knitting
T_{ak}	Tensile Strength after Knitting
Δ_k	Loss of Tensile Strength
mm	Millimetre
cm	Centimetre
m	Metre
g	Gram
kg	Kilogram
N	Newton
cN	Centi-Newton
J	Joule
KJ	Kilo-Joule
DIN	German Institute for Standardization
ISO	International Standard
Tex	Mass in Grams per 1000 Meters
$0°$	Wales Direction

Symbol	Designation
90°	Course Direction
E Modulus	Elastic Modulus
F_h	Fineness (in Tex) of Hybrid Yarn
n_r	Number of Reinforcing Filament-Roving
F_r	Fineness (in Tex) of Reinforcing Filament-Roving
f_r	Level of Feeding of Reinforcing Filament
n_m	Number of Matrix Filament-Roving
F_m	Fineness (in Tex) of Matrix Filament-Roving
f_m	Level of Feeding of Matrix Filament
G_r	Mass of Reinforcing Component
G_m	Mass of Matrix Component
V_r	Volume of Reinforcing Component
V_m	Volume of Matrix Component
ρ_r	Density of Reinforcing Component
ρ_m	Density of Matrix Component
T_{ht}	Theoretical Tensile Strength of Hybrid Yarn
T_{he}	Experimental Tensile Strength of Hybrid Yarn
T_r	Tensile Strength of Reinforcing Filament-Roving
T_m	Tensile Strength of Matrix Filament-Roving
Δ_h	Loss of tensile Strength (in %) of Component Materials by Commingling Process
T_{yl0°	Tensile Strength in Wales Direction of Loop Structure per 1 cm^2
T_{yl90°	Tensile Strength in Course Direction of Loop Structure per 1 cm^2

Symbol	Designation
T_{hel}	Experimental Tensile Strength of Finer Loop Yarn Before Knitting
n_{yl0°	Number of Straight Fiber Sections in Wales Direction of Unit Knit-Loop Structure
n_{yl90°	Number of Straight Fiber Sections in Course Direction of Unit Knit-Loop Structure
W	Number of Wales/cm
C	Number of Course/cm
Δ_{kl}	Degradation of Tensile Strength of Finer Yarn due to Knit looping
L_{yl}	Total Length of Finer Loop Yarns (m/m^2)
L_l	Length of Single Loop (in cm)
G_{yl}	Fabric Specific Weight (g/m^2)
t_l	Yarn Fineness (Tex) of Finer Loop Yarn
T_{yr0°	Tensile Strength of Multi-layered Knit Fabric in Wales Direction (per 1 cm^2)
T_{yr90°	Tensile Strength of Multi-layered Knit Fabric in Course Direction (per 1 cm^2)
T_{her}	Experimental Tensile Strength of Reinforcement Yarn Before Knitting
Δ_{kr0°	Degradation of Tensile Strength Due to Integration as Warp Inlay
Δ_{kr90°	Degradation of Tensile Strength Due to Integration as Weft Inlay
L_{yr0°	Total Length of Warp Inlay (m/m^2)
L_{yr90°	Total Length of Weft Inlay (m/m^2)
G_{yr0°	Weight of Warp Inlay (g/m^2)

Symbol	Designation
G_{yr90°	Weight of Weft Inlay (g/m^2)
G_{yr}	Total Weight of Multi-layered Reinforcement Structure (g/m^2)
t_{r0°	Fineness (Tex) of Warp Inlay
t_{r90°	Fineness (Tex) of Weft Inlay
w	Width (in cm) of Multi-layered Knit Fabric
T_{f0°	Tensile Strength of Multi-layered Knit Fabric in Wales Direction for Fabric Width w
T_{f90°	Tensile Strength of Multi-layered Knit Fabric in Course Direction for fabric width w
G_f	Total Weight of Multi-layered Knit Fabric (g/m^2)
T_c	Tensile Strength of Knit Composite
E_c	Tensile Modulus of Knit Composite
η	Efficiency Factor of Krenchel
σ_r	Tensile Strength of Reinforcement Component
σ_m	Tensile Strength of Matrix Component
E_r	Tensile Modulus of Reinforcement Component
E_m	Tensile Modulus of Matrix Component
Δ_{ct}	Degradation of Tensile Strength of Knit Composite
Δ_{ce}	Degradation of Tensile Modulus of Knit Composite

Chapter 1

Introduction

Climate model projections summarized in the latest IPCC report [1] indicate that the global surface temperature is likely to rise 1.1°C to 6.4°C further during the 21st century. The uncertainty in this estimate arises from the use of models with differing sensitivity to greenhouse gas concentrations and the use of deviating estimates of future anthropogenic greenhouse gas emissions. However in the 34th summit, the G8 countries have committed to limit global warming to 2°C and reduce 80% of their greenhouse gas emissions by 2050. The federal German government's contribution to the international climate agreement proposed to reduce 40% of CO_2 emissions by 2020, which would bring the level down lower than that of 1990. The greatest challenge to achieving such an ambitious objective is the commitment to research to find exceedingly economical and energy efficient solutions. The efficacy of the energy policy of the German federal government lies in the attainable synergy of the following three objectives; tenable energy supply, cost effectiveness and environmental compatibility. This means, the investments of the energy and industry sectors must be on reliable and competitive conditions. Simultaneously, transparent and reliable framework conditions and cost-effective solutions are indispensable for the consumers for their consumption and investment decisions [2–4].

Worldwide CO2 emissions are rising rapidly due to the combustion of fuel by all modes of transport. They currently amount to approximately 24% of the anthropogenic CO2 emissions. In order to preclude such emissions effectively, intelligent applications of textile reinforced composites in the automotive industry are key. They offer a great potential for reducing fuel consumption and CO_2 emissions by providing up to a 70% reduction in body weight compared to steel and at least 30% to aluminium. The environmental friendliness of a car, however, is based not only on the reduction of fuel consumption and CO_2 emissions. It also includes the entire life cycle of a vehicle from environmentally friendly manufacturing processes to its end disposal [5, 6]. The aviation industry is also showing a clear upward trend in the use of composite materials, which are produced mainly as unidirectional (UD) prepreg by tape laying process. The potential of textile reinforced composite structures is still far from exhausted. Studies conducted by Boeing indicate that a 38% composite structural weight can result in a 40% reduction in empty weight, 39% reduction in wing area and a 33% fuel savings for the same mission-profile when compared to an aircraft of conventional metal construction [7, 8].

Consequently, the lightweight textile reinforced composite materials are oriented toward a growing market. A significant increase rate of 15% in the global market for textile reinforced composite materials has been forecasted. Based on the figure alone, that in 2005 the five largest automobile markets of the EU registered a total of 13.2 million cars, a market of approximately 2.6 billion Euros could be calculated for textile reinforced composites when only 1% of sales is generated from textile reinforced composites. The Figure 1.1 illustrates a clear trend of promising material systems for lightweight economic designs, especially in the automotive industry. However, the breakthrough in the use of reinforcement fabrics for composites in vehicle and mechanical engineering will only be achieved when the high requirements concerning the performance and the intelligence of the components, the environmentally friendly complete life cycle from manufacturing to disposal, the ease of repairing and recyclability, the reproducibility and suitability to medium- and high-volume series production along with a fully automated economical manufacturing are met [9–11].

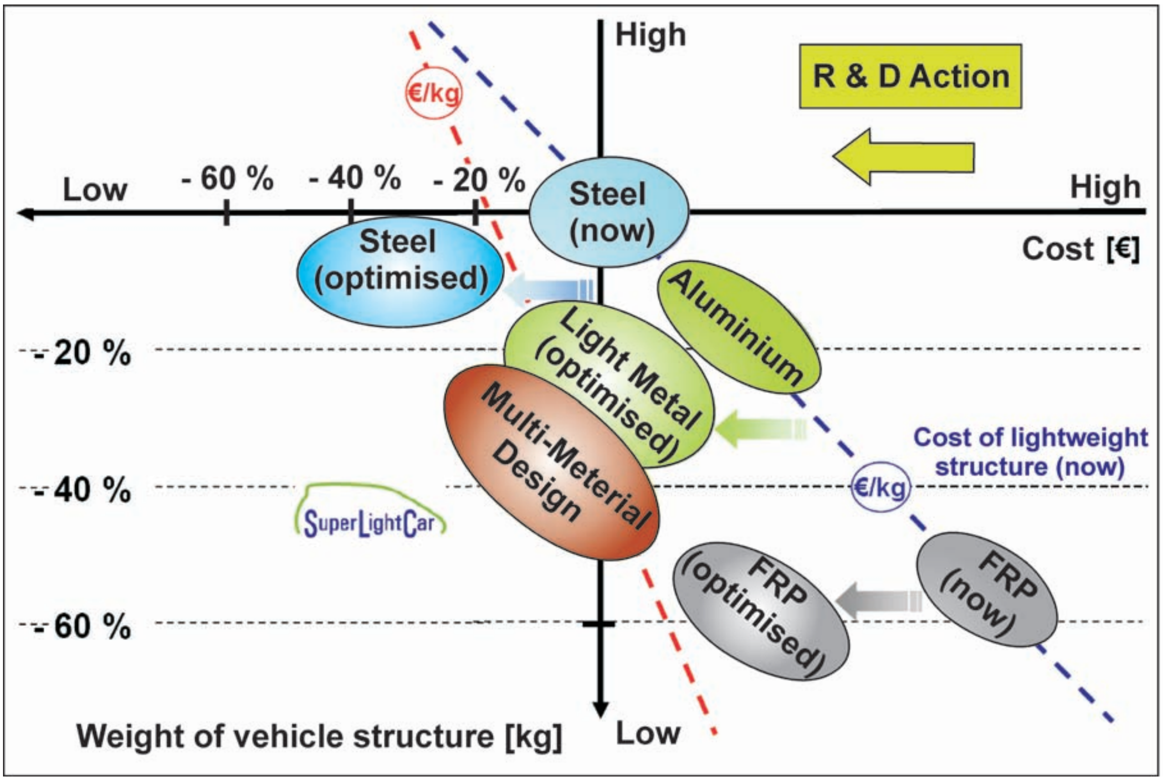


Figure 1.1: Herder for the lightweight economic concept [9]

Textile reinforced composites are fiber-reinforced composites whose reinforcement structures are characterized by the fiber orientation. Unlike the conventionally used isotropic materials, the material properties of textile reinforced composites can be specially customized to accommodate particular load situations by modifying the fiber architecture and material combinations. These composites are best suited for any design program that demands weight reduction, precision engineering, finite tolerances, and the simplification of parts in both production and operation. Textile reinforced composites are considered to be cheaper, faster, and easier to manufacture than cast aluminium or steel and generally maintains better tolerances and material strength [12–14].

However, thermoplastic composites are comprised of at least one reinforcement material and a thermoplastic polymer as matrix. These composites show distinct advantages over thermoset composites. Due to their high fracture toughness, easy recycling, short processing time, various forming possibilities, weld-ability, low cost and resistance to media and corrosion, they appear to be more promising for industrial applications [12–18]. But, conventional thermoplastic composite manufacturing routes are two stage processes. Firstly, a precursor material is formed, i.e. commingled fibers, prepregs, powder impregnated tows, fiber impregnated thermoplastic, short and long fiber reinforced polymer pellets, etc. The second step in the process is forming the component into the final product by applying high pressure and high temperatures. The aim of the aforementioned process is to coat the reinforcing fibers with the thermoplastic and form the desired shape. Nevertheless, commingled hybrid yarns consisting of reinforcement and matrix filaments are soft, flexible, drapeable and are available at a low cost, which makes them a forerunner for thermoplastic composite manufacturing [19–21]. The reinforcement component of the hybrid yarn is generally high performance fibers such as glass, carbon and aramid fibers. Glass fibers are used extensively due to the optimized cost versus mechanical performance. The thermoplastic matrix is used to fix the reinforcement components in a defined order to improve the bearing of applied forces, to ensure good adhesion between the fibers and matrix material and to develop low cost products, especially for the automotive industries [22–25]. The use of glass (GF) and polypropylene (PP) filaments in hybrid yarns in a volume combination of 52% and 48% respectively is reported to optimize the mechanical properties of textile reinforced thermoplastic composites [26].

Textiles generally produced by braiding, weaving and other uni-directional techniques are primarily used as semi-finished textiles in composites for the aerospace and automotive industries. The variety of existing and potential applications of reinforcing textiles on the basis of innovative and economical manufacturing processes is immense. However, innovative 3D spacer fabrics show a great potential as textile preforms in high performance composites if they are manufactured in a single stage manufacturing process using high performance fibers. The excellent mechanical properties, such as high strength, stiffness, damage tolerance in impact loading, etc. along with the economical single stage manufacturing process make them a precursor for 3D textile reinforced composite applications [12–22, 26].

Spacer fabrics are complex 3D constructions made of two separate fabric layers connected vertically with pile yarns or fabric layers. The conventional spacer fabrics composed of two surface layers bound with pile yarns are generally manufactured using weaving and knitting technologies. However, due to inferior mechanical properties, such as elasticity and deformability under applied loads, conventional spacer fabrics are not suitable for high performance composite applications. Moreover, the restricted distance between the plane layers contribute to the drawbacks of such spacer fabrics. One solution is to connect the planes by means of fabric layers instead of pile yarns. So far, these 3D spacer fabrics are produced with sewing or adhesives using almost entirely flat textiles. The used sewing threads or adhesive lead to inhomogeneity in the structure, which makes the composite structure weedy. Moreover, the additional production stages raise the manufacturing cost and limit the product to niche applications. On the other hand, the weaving technique is not considered to be feasible for 3D textile manufacturing due to the huge investment costs and complex manufacturing processes along with process limitation for manufacturing of complex shaped structures. Besides, the mechanical properties of woven fabric reinforced composites are adversely affected by the interlacing of very brittle reinforcement yarns in weaving [12–19, 22, 27–29].

Modern flat knitting machines are capable of manufacturing 3D complex shaped engineering structures cost effectively. Unique technical features which allow rapid and complex production include individual needle selection capability, the presence of holding down sinkers, presser-foots, racking, transfer, adapted feeding devices combined with CAD system, modern programming installations, etc. Furthermore, the flexibility of the knitting process in combination with the possibility of integration of reinforcement yarns into fabric structures is capturing the attention of many researchers. Also, the additional cutting processes could be completely eliminated by knitting the textile preforms in "near to net" form with the help of the "Fully-Fashion" technique. However, exceeding the aforementioned technological advancements of flat knitting, the 3D complex shaped innovative spacer fabrics are not developed yet for high performance composites because of the inadequate machine and manufacturing technologies required for such multi-layer 3D spacer fabric knitting [12–20, 26–32]. Moreover, knitted fabrics made from high performance fibers (e.g. glass, carbon) are prone to some difficulties during knitting because of high stiffness, high coefficient of friction and high brittleness of such materials. Nevertheless, knitted composites are generally considered to have inferior mechanical properties due to their highly looped fiber architecture. Conversely, the integration of reinforcement yarns into the knit structures is inevitable in order to improve the mechanical properties for the application in high performance composites [26, 33–39]. Even so, if the innovative 3D spacer fabrics consisting of reinforced surface and connecting layers are developed on a flat knitting machine, waste can be reduced and faster production times can be achieved. These 3D spacer fabrics are expected to show superior mechanical properties. For example, very much improved tensile and compression characteristics, flexural properties and energy absorption can be expected, which would make them suitable for lightweight applications. Future applications of composites made from innovative 3D multi-layer spacer fabrics involve the replacement of conventional panel structures, which are mainly metallic/ fiber-reinforced plastic surfaces bonded by adhesives with metallic/ polymeric honeycomb or foam cores used currently in aircraft, spacecraft, transport vehicles, marine applications and infrastructures, lift cabins, ballistic protection for buildings and combat vehicles, etc. [12–20, 26–30].

Within this background, the present research focuses on the development of flat knitting technology and manufacturing process for innovative 3D spacer fabrics to be used as complex shaped load-adapted textile preforms in high performance composite applications. With the aim of manufacturing the thermoplastic textile composites the novel 3D spacer fabrics should be developed using the exemplar GF-PP commingled hybrid yarn. In order to develop compatible textile preforms suitable for 3D structures for complex shaped composite components, different geometrical shapes of 3D spacer fabrics consisting of surface layers connected with the same should be manufactured on flat knitting machines as proposed by the new developments. The reinforcement yarns must be integrated into spacer fabric structures (in both surface and connecting layers) as multiple layers in order to improve the mechanical properties for application in high performance composites. Moreover, for structural health monitoring, the integrated sensor networks within the spacer fabric structure should be created simultaneously while knitting the 3D spacer fabric with innovative flat knitting technology. Furthermore, the influence of the integration methods of reinforcement yarns (fiber-arrangements) on the mechanical properties of reinforcement yarns, 2D knit fabrics and 2D knit composites should be investigated. Finally, the mathematical analyses should be carried out in order to predict the tensile properties of the hybrid yarn, multi-layered 2D knit fabric and 2D knit composite.

Chapter 2

Flat knitting technology

2.1 Basic principles and structures of flat knitting

Knitting is a conversion system in which yarn loops are intermeshed to form a fabric and accounts for more than 30% of total fabric production worldwide. Knitting is classified into two fields, weft knitting and warp knitting. In weft knitting, loops are formed in a horizontal direction, whereas in warp knitting, loops are formed in a vertical direction (Figure 2.1). Weft knitting is more resilient, more open and has additional design possibilities as compared to warp knitting. Weft knitting can be divided into circular knitting and flat knitting. In the circular knitting machine, needles are set radically or parallel in one or more circular beds. On the other hand, a flat knitting machine employs straight needle beds carrying independently operated needles, which are usually of the latch type [31, 32, 40–42].

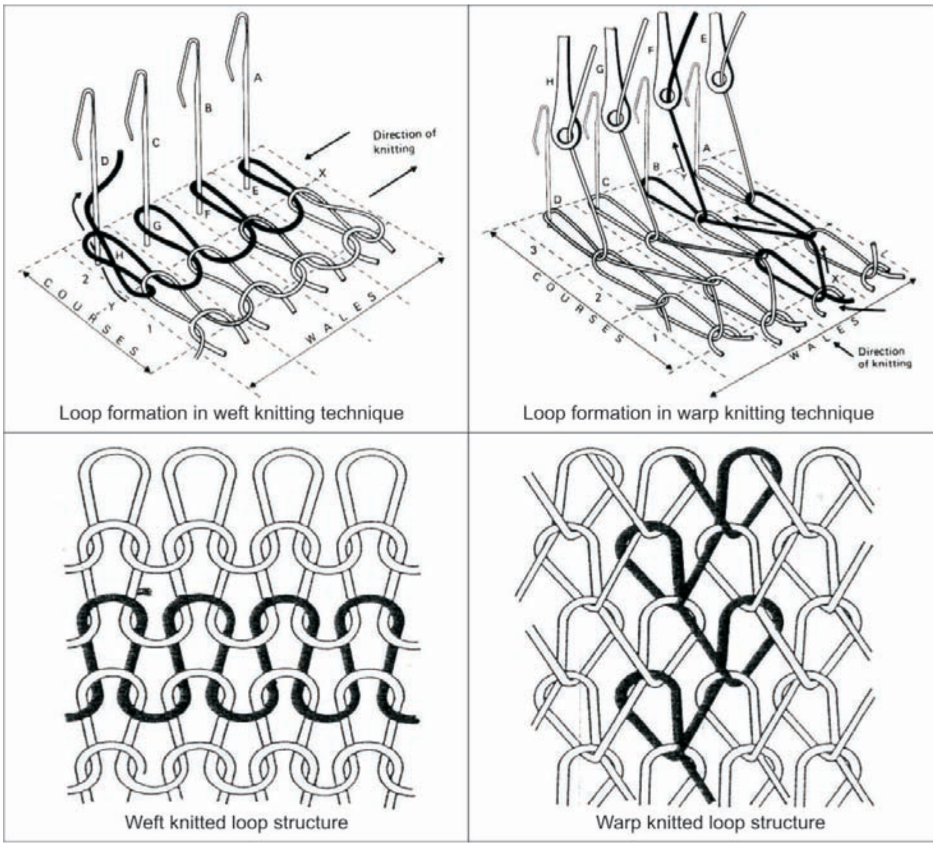


Figure 2.1: Comparison of weft and warp knitting [31]

Flat knitting is a method for producing knitted fabrics wherein the work is turned periodically, for example, the fabric is knitted from alternating sides. Flat knitting machine is very flexible and allows complex stitch designs, shape knitting and precise width adjustment. A flat knitting machine consists of at least 2 flat needle beds arranged in an upside-down "V" formation. These needle beds can be up to 2.5 metres wide and needles are mounted in the needle grooves of needle beds. Generally, flat knitting gauges range from E5 to E14 which allow wide ranges of yarn counts to be used. Carriage, also known as Cambox or Head, which is equipped with different knitting cams and mounted on the needle beds, moves backwards and forwards across the needle beds. Thus, the needles are driven selectively by the respective cams to form the knit, tuck or transfer stitches. Normally, yarns are supplied from cones or spools and stored in the yarn storage. These yarns are guided by the yarn feeders through the yarn controlling as well as tensioning devices to the knitting zone where loops are formed and intermeshed by the mutual action of needles and sinkers. The knitted fabrics are delivered by the take down rollers and placed in storage section at the bottom of the machine [31, 32, 41, 43, 44]. The basic construction and knitting zone of a flat knitting machine are shown in Figure 2.2, whereas the knitting action is in Figure 2.3.

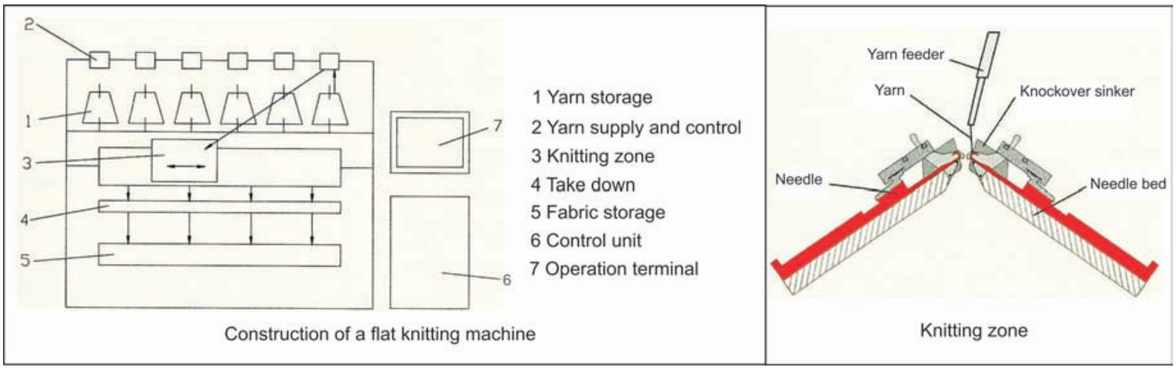


Figure 2.2: Basic construction and knitting zone of flat knitting machine

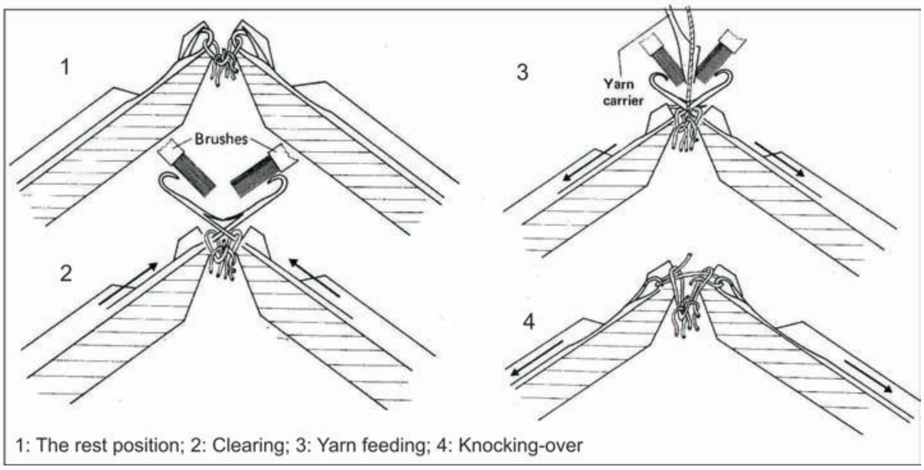


Figure 2.3: Knitting action of V-bed flat knitting machine [31]

However, different stitches, for example, knit loop, tuck stitch and float stitch, could be produced by varying the sequence of the needle loop intermeshing in flat knitting. A knit loop stitch is produced when a needle receives a new loop and knocks-over the old loop that it held from the previous knitting cycle. On the other hand, a tuck stitch is produced when a needle holding its loop also receives the new loop, which becomes a tuck stitch because it is not intermeshed through the old loop, but it is tucked behind it on the reverse side of the stitch. Then again, a float stitch is an old loop that the needle has retained and it is not released and knocked-over until the next, or a later, yarn feed. In addition, the drop stitch and plating technique are also used to design the knit structures. Besides, the additional yarns could be integrated into knit structures as weft and warp inlays to increase compactness and mechanical performance of fabrics [31, 32, 41]. The structural elements of knit fabrics by flat knitting are shown in Figure 2.4.

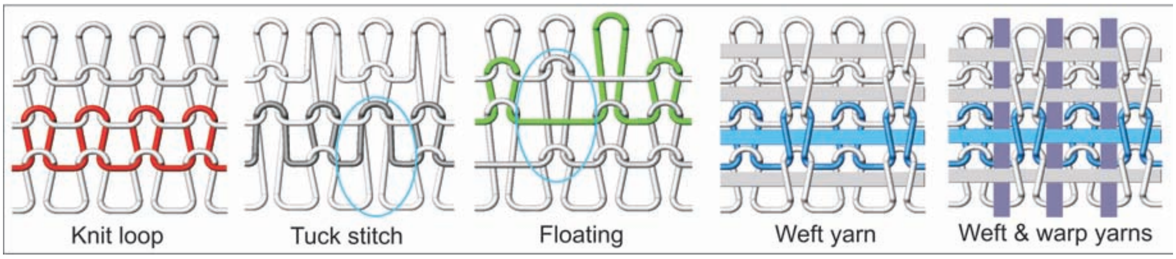


Figure 2.4: Structural elements by flat knitting

Nevertheless, four primary base fabrics- plain, rib, interlock and purl- are the base structures from which all flat knitted fabrics are derived. Plain is produced by the needles knitting as a single set, drawing the loops away from the technical back and towards the technical face side of the fabric. Conversely, rib requires two sets of needles operating in between each other so that the wales of face stitches and wales of reverse stitches are knitted on each side of the fabric. But, interlock was originally derived from rib but requires a special arrangement of needle knitting back-to-back in an alternative sequence of two sets, so that the two courses of loops show wales of face loops on each side of the fabric exactly in line with each other, thus hiding the appearance of the reverse loops. On the other hand, purl is the only structure having certain wales containing both face and reverse meshed loops [31,32,41]. These four primary base flat knitted structures are presented in Figure 2.5.

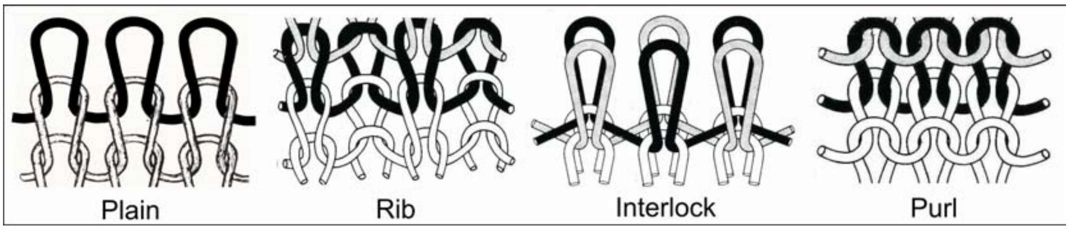


Figure 2.5: Primary base structures by flat knitting [31]

2.2 Automatic power flat knitting machine and its modern features

Over the last thirty years, many innovations and refinements in knitting technology have gradually evolved and combined to transform the mechanically-controlled V-bed machine into a computer-controlled, highly efficient and versatile knitting machine, not only for cut-and-sew knitwear, but also for integrally-shaped panels and whole garments. Main intention of developing such automated flat knitting technology was the automatically knitting of garments in industrial scales with little or no further human intervention. However, a brief overview of some of the modern features of a fully automated flat knitting machine is presented in this section [31,32,41–47].

2.2.1 CAD system and modern programming installation

In general, knit patterns can be created on the CAD (Computer-Aided Design) system. This data can be transferred to the flat knitting machine and the machine can be operated. Such CAD system is a totally integrated knit production system that allows all phases including planning, design, evaluation and production. Specifically, the loop simulation program permits quick estimation of knit structures without any kind of actual sample making. The program provides an opportunity to see knit problems and try out diverse knit structures on the computer before beginning actual knitting [45, 48, 49].

2.2.2 Electronic controls

The electronically-controlled power flat knitting machine offers quick response to size, style and pattern changes with versatile and infinitely variable adjustment of its electronically-controlled functions under the guidance of CAD-data and the back-up support of its memory. It is therefore more able to meet the exacting requirements for knitting shaped garments efficiently. In contrast, the mechanically-controlled power flat machine is time-consuming and costly during machine changes and its limited facilities provide less scope for adjustment [31, 45].

2.2.3 Individual needle selection capability

Modern flat knitting machine offers the individual needle selection capabilities, in which a wide range of designs and colour-combinations are possible. Along with the needles some additional selectors are mounted on the needle beds, which allow carriage to guide them in versatile ways in knitting. Moreover, the electro-magnetic selecting device in carriage can operate any single needle according to the knit pattern [31, 48, 49].

2.2.4 Fully-fashioning or shape-knitting

The fully-fashioning process allows the separate creation of shaped body parts of garments by increasing and decreasing the number of loops and this eliminates the additional cutting operating leading to the reduction of wastage. To achieve fully-fashioned knitting, loop transfer is necessary in which stitches moves from the needles on which they were made to other needles [31, 45, 48, 49].

2.2.5 Seamless knitting (knit and wear)

Seamless knitting creates a complete garment by several feeders with no cutting and sewing processes. For example, three different tubes (one body part and two sleeves) could be knitted separately on the needle beds and could be joined by knitting to create a complete garment. Thus, seamless knitting has the capability of cost saving with reduced production time by removing post-knit processes such as the linking or sewing and cutting operation [31, 45, 48–50].

2.2.6 Stitch pressing-down devices

The objective of presser foot and other similar devices (such as knock-over bits and holding down sinkers) of modern flat knitting machine is to keep the old loops (fabric) low down on the needle stems. They are thus prevented from rising and staying on the latch spoons as the needles rise for clearing or yarn feeding. This ensures a “clean” knitting action, irrespective of the variable tensions within the knitted structure or the lack of take-down tension operating onto the fabric from below [31].

2.2.7 Multi-gauge technique

Multi-gauge technique allows knitting of both zones having coarse and fine gauge stitches. This involves a combination of techniques, including half-gauging, using different numbers of yarn ends, intarsia zoning, and blocks of different gauges of needles each working with its corresponding count of yarn and yarn carrier [31, 45, 48, 49].

2.2.8 Advanced take-down system

Modern machines have computer-programmed, positively-driven take-down system whose operation is synchronised with that of the requirements of the knitting programme and provides pre-determined fabric tension as required [31].

2.2.9 Needle bed racking

Needle bed racking is very common for modern flat knitting and it is being practiced in order to transfer the loops in fully fashion and seamless knitting. In addition, racking is also used to make the knit design fashionable. A maximum racking distance of 2 inches in both directions, in some cases on both beds, is available [31].

This chapter has provided an overview of the fundamentals, structures of flat knitting as well as the modern features of automatic power flat knitting. The discussion on the epic features of modern flat knitting technology forwards a clear view point on the high potentiality of innovative textile structures by flat knitting with the highest level of flexibility. Various 2D/3D innovative engineering textile structures could be developed by modern flat knitting, where the usage of hybridized as well as functional materials would be the best solution to create function-integrated multi-material design. Nevertheless, even having very promising development scopes, the flat knitting technology has not been practiced yet enough in the field of technical textiles. Therefore, the intention of present research is to explore the flat knitting by developing new technologies as well as manufacturing processes for innovative 3D spacer fabrics applicable as load-adapted textile preforms in high performance composites. However, the next chapter digs deeper into the manufacturing of textile reinforced composites, significance of thermoplastic composites, manufacturing and application of spacer fabrics and panel structures in lightweight application, through in-depth analysis of the contemporary literature.

Chapter 3

State of the Art of 3D Spacer Fabric for Composite

3.1 Textile reinforced composites

Textile reinforced composites are fiber-reinforced composites whose unit reinforcement structures are characterized by the fiber orientation. Unlike the conventionally used isotropic materials, textile reinforced composites can be specifically customised in terms of their material properties for particular loading situations by modifying the fiber architecture and material combinations. Textiles generally produced by braiding, weaving and other uni-directional techniques from high performance fibers are primarily used as textile preforms in high performance composites, especially for aerospace and automotive industries [12, 13]. However, fibers, because of their small cross-sectional dimensions, are not directly usable in engineering applications. They are, therefore, embedded in matrix materials to form fibrous composites. The matrix materials, which are generally thermoset and thermoplastic polymers, serves to bind the fibers together, transfer loads to the fibers, and protect them from against environmental attack and damage due to handling.

Nevertheless, textile reinforced composites have become the most important class of composite materials, because they are capable of achieving high mechanical performances at very low weights. Consequently, textile reinforced composites pose a great potential as a competitive alternative to conventional isotropic metallic structures in lightweight applications [51–53].

Subsequently, the textile reinforced composite materials are part of a significantly expanding market, where the global rate of increase has been achieved about 10% per year and forecasted about 15% per year in the following years. As of 2009, the 42 billion $US composite industry consisted of over 3000 companies. The major dynamic market segments of high performance textile reinforced composites are automotive, aerospace, wind energy, ship building industries, etc. The exemplarily cost comparison of different materials based on weight and strength has been shown in Figure 3.1 [54, 55].

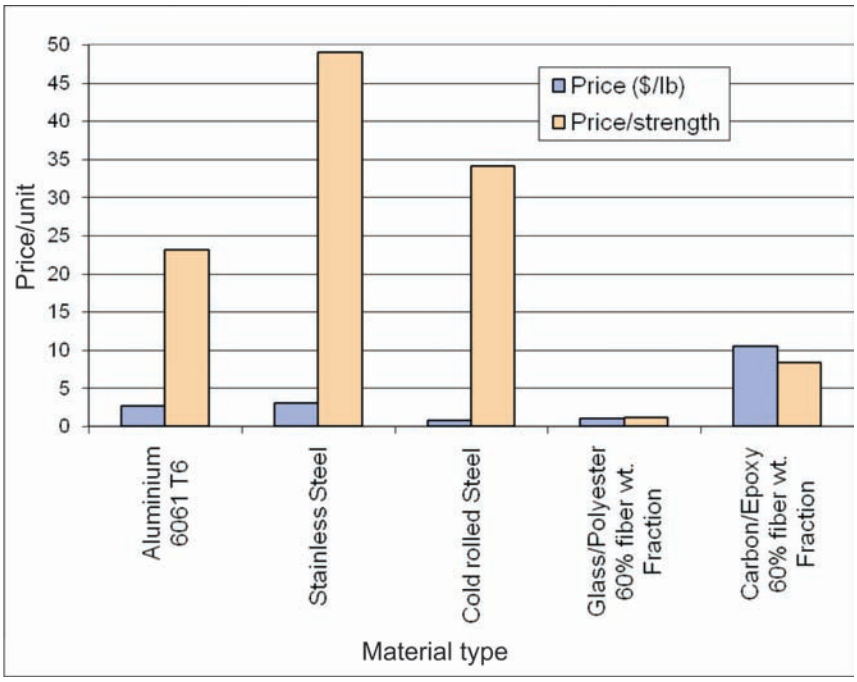


Figure 3.1: Cost comparison of different materials based on weight and strength [54, 55]

3.1.1 Manufacturing of textile composites

Fabrication of textile composites depends on the chemical nature of the matrix materials, which are generally classified into two groups, for instance, thermoset and thermoplastic polymers. The both composite fabrication methods are described in brief in the following subsections [51–53].

3.1.1.1 Thermoset composite manufacturing

For a thermoset polymeric matrix material, the moulding event is a curing reaction that is initiated by the application of additional heat or chemical reactivity such as organic peroxide. There are two families of processing routes for thermoset composite manufacturing: pre-preg and liquid moulding. Pre-preg is a term for pre-impregnated composite fibers. These usually take the form of a weave or are unidirectional. They already contain an amount of the matrix material used to bond them together and to other components during manufacturing. The pre-preg is mostly stored in cooled areas since activation is most commonly done by heat. Hence, composite structures built of pre-pregs will mostly require an oven or autoclave to cure out. However, the cost, both in terms of the initial cost of the material and its storage and cure requirements (time consuming: several hours), is much higher in pre-impregnated composites manufacturing [51].

On the other hand, liquid moulding is arguably the most flexible, combining the small batch flexibility with low emissions and higher quality levels of pre-preg, without the on-costs associated with those materials. Thermoset matrix materials generally come in liquid form, and when mixed with a catalyst, a chemical reaction occurs forming a solid. And these liquid matrixes are injected to the textiles before curing following different injection methods, for instance, resin transfer moulding (RTM), vacuum infusion (VI), structural reaction injection moulding (SRIM), etc. Thermoset molecules crosslink with each other during curing, thus once cured, they cannot change. That is why thermoset composites are not recyclable. Besides, thermoset composite manufacturing technique is considered only for small to medium series of production because of prolonged process-cycle [51, 52].

3.1.1.2 Thermoplastic composite manufacturing

Thermoplastic composites are composites that use thermoplastic polymers as matrix materials. The processing steps for the manufacture of thermoplastic composites are much simpler than for thermoset. The thermoplastic component has to be intimately mixed with the fibres, melted and formed into the final shape. No chemical reactions, as with thermoset materials, are involved [51]. However, the development of thermoplastic composites has been restricted due to the greater difficulty of this fibre impregnation with thermoplastic melts when compared to thermoset resins. This is due to the higher viscosities of thermoplastic melts which are between 10-100 Pa.s. as compared to 0.2-2 Pa.s. for thermoset resins [55]. Conventional thermoplastic composite manufacturing routes are two stage processes. Firstly, a precursor material is formed using high performance fibers and thermoplastic polymers. For example, commingled fibers, prepregs, powder impregnated tows, fiber impregnated thermoplastic, short and long fiber reinforced polymer pellets, etc., whereas commingling process is more suitable for the homogeneous mixing of the components, versatility of manufacturing process, cost-effective process and the manufacturing of soft, flexible and drape-able yarns [56–59]. The secondary process is forming the component into the final product applying high pressure and high temperature. In this process, temperature is increased above the melting temperature, so that thermoplastic matrix polymers become melted during the final conversion process. The application of pressure is to give intimate contact and hence heal adjacent yarns and plies, reducing void content, completes consolidation followed by cooling, under pressure, to solidify and crystallise the matrix to finish the cycle (Figure 3.2) [51–53, 55].

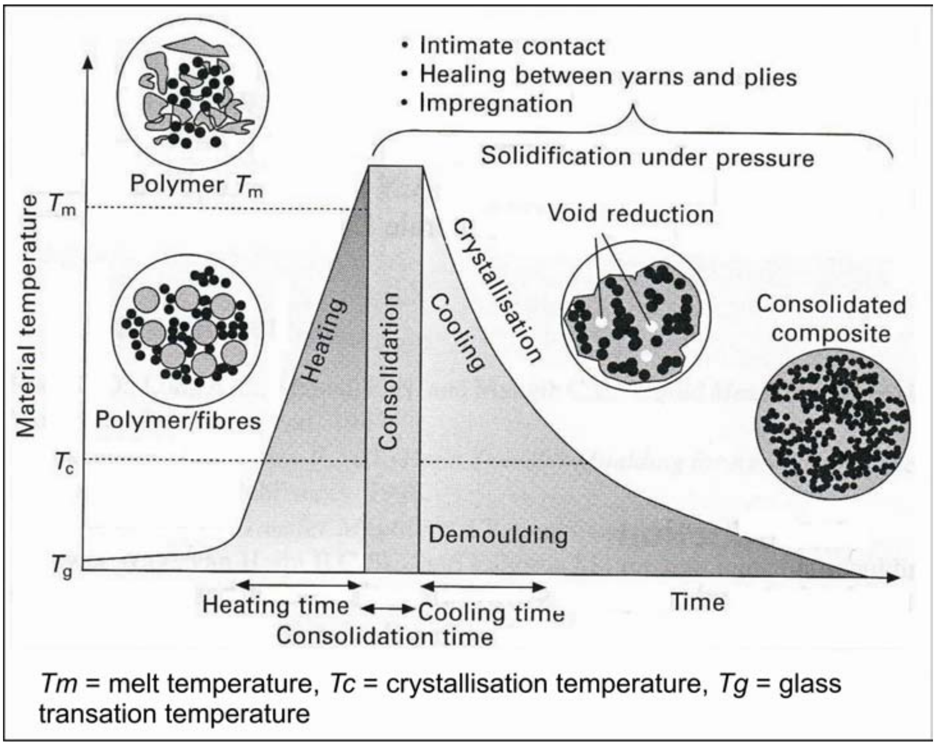


Figure 3.2: Thermal cycle for thermoplastic composite processing [52]

3.1.2 Advantages of thermoplastic composites

Thermoplastic composites show distinct advantages over thermoset composites. Though thermoplastic polymers tend to have higher melt viscosities necessitating higher pressures, however, thermoplastic moulding can be carried out non-isothermally, i.e. a hot melt into a cold mould, in order to achieve fast cycle times, for example, within few minutes whereas it is several hours in most cases for thermoset process. Moreover, thermoplastic composites offer increased recyclability and can be post-formed or reprocessed by the application of heat and pressure. Furthermore, thermoplastic composites are renowned for their superior impact and damage resistance properties. In addition, thermoplastic composite manufacturing is considered as more environmental friendly process than thermoset manufacturing, since approximately 65% used thermoset matrix materials are unsaturated polyesters. Also, thermoplastic composites are more advantageous in terms of the resistance to medias and corrosion. Besides, over 90% of polymers used in composites are thermosets and there is still a niche market for thermoplastic composites, especially in cost sensitive premium market, for instance, automotive, air- and aerospace industries [51–53, 55, 56].

Therefore, it can be inferred from the above discussion, the thermoplastic composites are being considered as more advantageous than thermoset composites. Thermoplastic composites could be a very good choice for lightweight industries, where the thermoset composites are still questionable in different issues, such as, recyclability, cost-effectiveness, consolidating in complex-shaped, complexity of consolidation process, eco-friendliness, etc.

Nevertheless, keeping in view the potentiality of thermoplastic composites, it seems worthwhile to discuss on the hybrid yarns for thermoplastic composites, since the construction of hybrid yarn is considered to be the most effective method for homogenous mixing of the reinforcing and matrix components. The next section, therefore, underlines the hybrid yarn for textile reinforced thermoplastic composite.

3.2 Hybrid yarn for textile reinforced thermoplastic composite

Hybrid yarns are the blended yarns which are made of at least two different components in the form of filaments and/ or fibers. It is advantageous for fiber-reinforcement materials if the mixing of reinforcement and matrix components is already effected in the yarn structure. Hybrid yarns consisting of high performance fibers and thermoplastic matrix materials could be manufactured by various methods of yarn manufacturing technology [57–59]. A brief overview on the high performance fibers, thermoplastic matrix materials and the various methods of hybrid yarns manufacturing have been presented in the following subsections.

3.2.1 High performance fibers

A great majority of materials are stronger and stiffer in the fibrous form than as a bulk material. A high fiber aspect ratio (length-diameter ratio) permits very effective transfer of load via matrix materials to the fibers, thus taking advantage of their excellent properties. Therefore, fibers are very effective and attractive reinforcement materials. Glass, carbon and aramid fibers, which are the most common high performance fibers used as reinforcing materials for composites, are discussed in this section [52].

3.2.1.1 Glass fiber (GF)

Glass fibers are the most common of all the reinforcing fibers for polymer matrix composites. The principal advantages of glass fibers are the low cost and high strength. Glass fibers are developed amorphously where the atoms create 3d-network with strong covalent bonds. However, glass fibers have poor abrasion resistance, which reduces their usable strength. They also exhibit poor adhesion to some polymer matrix resins, particularly in the presence of moisture. To improve adhesion, the glass fiber surface is often treated with chemicals called coupling agents (mostly silanes). There are different types of glass fibers (Type- E, -R, -S, -T, etc.). As Glass fiber type-E is very economical, it is mainly used to reinforce the plastic materials. But for higher mechanical and thermal properties, glass fiber type-R, -S and -T are used to reinforce the composite materials [18, 52].

3.2.1.2 Carbon fiber (CF)

A naturally abundant non-metallic element that occurs in many inorganic and in all organic compounds, exists freely as graphite and diamond and as a constituent of coal, limestone, and petroleum, and is capable of chemical self-bonding to form an enormous number of chemically, biologically, and commercially important molecules. Carbon fibers are particularly suitable for applications in lightweight construction for its higher mechanical properties. However, currently available carbon fibers are made using one of the three precursor materials: polyacrylonitrile (PAN), pitch and rayon. The PAN based carbon fibers are lower in cost with good properties. They are the dominant class of structural carbon fibers and are used widely in high performance lightweight applications. Pitch-based carbon fibers generally have higher stiffness and thermal conductivities, which make them useful in satellite structures and thermal-management applications, such as space radiators and electronic enclosures. Rayon-based carbon fibers, due to their low thermal conductivity, are useful for insulating and ablative applications such as rocket nozzles, missile reentry vehicle nosecones and heat shields [18, 52].

3.2.1.3 Aramid fiber (AF)

The name "Aramid" is a shortened form of "aromatic polyamide". They are fibers in which the chain molecules are highly oriented along the fiber axis, so the strength of the chemical bond can be exploited. The aramid fibers possess unique properties. Tensile strength and modulus are substantially higher and fiber elongation is significantly lower for aramid fibers than those of other organic fibers. However, they are poor in characteristics in compression. Aramid fibers are used in aerospace and military applications, for ballistic rated body armour fabric, in bicycle tires, and as an asbestos substitute. The important mechanical properties of common high performance fibers are represented in Table 3.1 [52].

	E-Glass	**S-Glass**	**Carbon (PAN)**	**Aramid (Kevlar 29)**
Tensile strength (MPa)	3448	4585	1925-6200	2760
E Modulus (GPa)	72.4	85.5	230-595	62
Elongation at break (%)	4.5	3.8	0.4-1.2	3.4
Density (g/cm^3)	2.6	2.53	1.77-1.96	1.44
Diameter (μm)	3-20	8-13	5-8	12

Table 3.1: Mechanical properties of high performance fibers [52]

3.2.2 Thermoplastic matrix materials

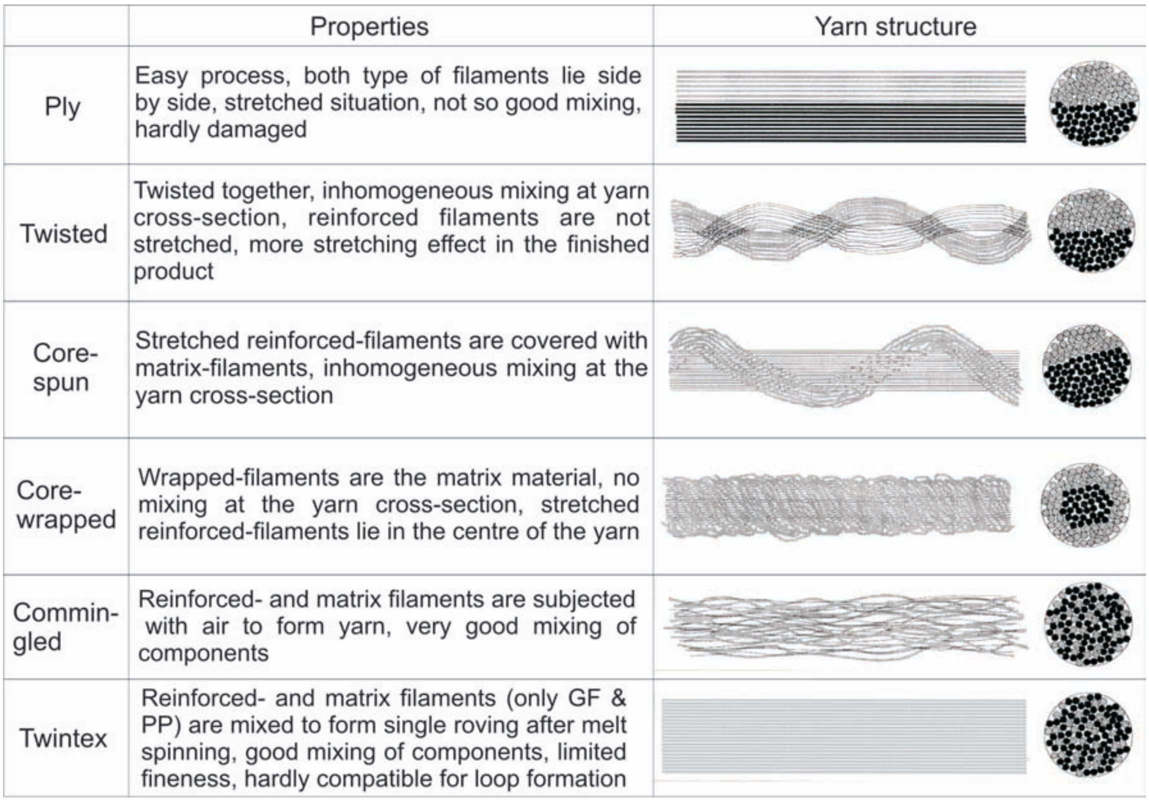
Reinforced fibers are embedded with a matrix material to produce reinforced composite materials, since fibers acting alone cannot transmit loads from one to another due to their small cross-sectional dimensions. The roles of the matrix materials in the reinforced composite materials are to fix the reinforced fibers in a defined order, to carry the applied forces on the reinforced fibers, to ensure a good adhesion between fibers and matrix material, to support the reinforced fibers during compression stresses, to protect the reinforced fibers from medias (e.g. chemical media) and during shaping of the product. There are two types of matrix materials, thermosetting and thermoplastic matrix materials. However, matrix polymers those soften or melt on heating called thermoplastic matrix materials. Melting and solidification of these polymers are reversible, and they can be reshaped by means of heat and pressure. The fiber-reinforced composites with thermoplastic matrix materials show distinct advantages over thermoset composites, for instance, high fracture toughness, easy recycling, short processing time, various forming possibilities, weld-ability, low cost and resistance to medias, better pressure-, crease-, compressive behaviours etc. Table 3.2 presents the mechanical properties of important thermoplastic matrix materials [51, 52].

	PP	**PEEK**	**PET**	**PPS**
Tensile strength (MPa)	21-37	90-100	48-73	48-87
Elongation at break (%)	15-50	50	50-150	50-100
Density (g/cm^3)	0.90	1.32	1.3	1.35
Processing temperature (°C)	200-300	360-400	260-350	310-335
Glass transition temperature (°C)	-20	143	80	90
Melting temperature (°C)	175	343	250	285

Table 3.2: Important properties of thermoplastic matrix materials [51, 52]

3.2.3 Manufacturing of hybrid yarn

Hybrid yarns consisting of reinforcing and thermoplastic matrix materials as filaments are suitable in consolidation process in order to reduce the problems associated with high melt viscosity of thermoplastic matrix during impregnation. Hybrid yarns compatible for textile manufacturing process offer high potential for textile based thermoplastic composites, especially in high performance lightweight applications. These yarns can be produced following different manufacturing techniques, such as, plying, twisting, covered-core spinning, friction spinning, commingling and melt spinning [18, 57–59]. The Figure 3.3 represents the important properties and yarn structures of those hybrid yarn manufacturing processes.



	Properties	Yarn structure
Ply	Easy process, both type of filaments lie side by side, stretched situation, not so good mixing, hardly damaged	
Twisted	Twisted together, inhomogeneous mixing at yarn cross-section, reinforced filaments are not stretched, more stretching effect in the finished product	
Core-spun	Stretched reinforced-filaments are covered with matrix-filaments, inhomogeneous mixing at the yarn cross-section	
Core-wrapped	Wrapped-filaments are the matrix material, no mixing at the yarn cross-section, stretched reinforced-filaments lie in the centre of the yarn	
Commin-gled	Reinforced- and matrix filaments are subjected with air to form yarn, very good mixing of components	
Twintex	Reinforced- and matrix filaments (only GF & PP) are mixed to form single roving after melt spinning, good mixing of components, limited fineness, hardly compatible for loop formation	

Figure 3.3: Different manufacturing of hybrid yarns

However, in commingled hybrid yarn manufacturing, the reinforcing and matrix materials are intimately mixed in a nozzle by means of compressed air. This process is versatile and gives soft, flexible and drapeable yarn. A wide range of yarn finenesses along with various material combinations are possible by this commingling process. These features have made commingling technology suitable for hybrid yarn manufacturing, which is compatible for both textile preforming as well as thermoplastic consolidation processes. Consequently, such commingling technology puts forward tremendous potential in the production of cost-effective textile reinforced thermoplastic composites, especially for lightweight industries [58]. The method of commingled hybrid yarn spinning has been shown in Figure 3.4.

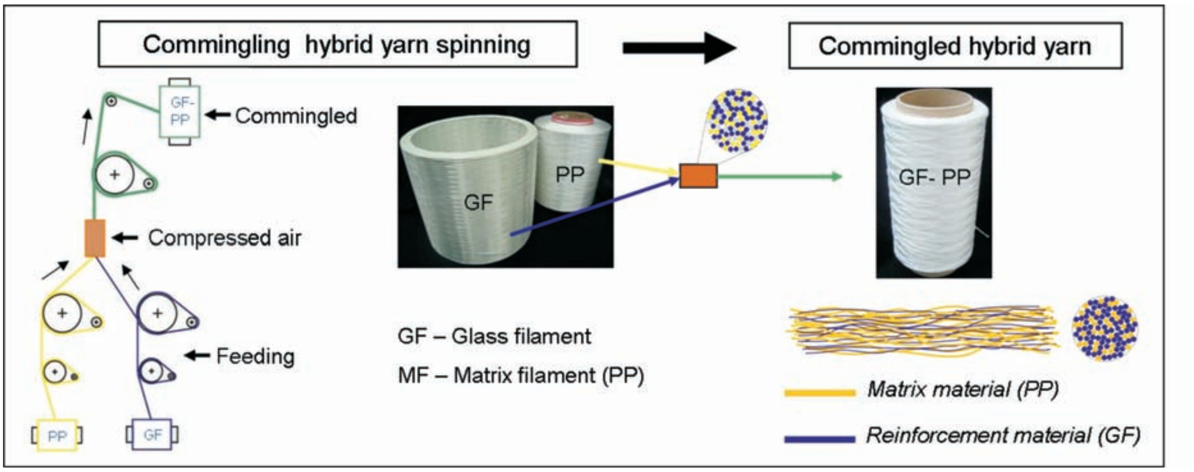


Figure 3.4: Commingled hybrid yarn spinning

3.3 Spacer fabrics

Spacer fabrics are complex 3D constructions made of two separate fabric layers connected vertically with pile yarns or fabric layers keeping hollow space between adjacent connecting yarns or layers. The conventional spacer fabrics, which are consisted of two surface layers bound with pile yarns, generally belong to the only existed category of spacer fabrics. The schematic of spacer fabrics are shown in Figure 3.5. Spacer fabrics are manufactured usually by different methods, for examples, by weaving, braiding, stitching, warp knitting and weft knitting [12, 13, 15–18, 22, 26–30]. Further discussion on the different manufacturing of spacer fabrics are presented in the following subsections.

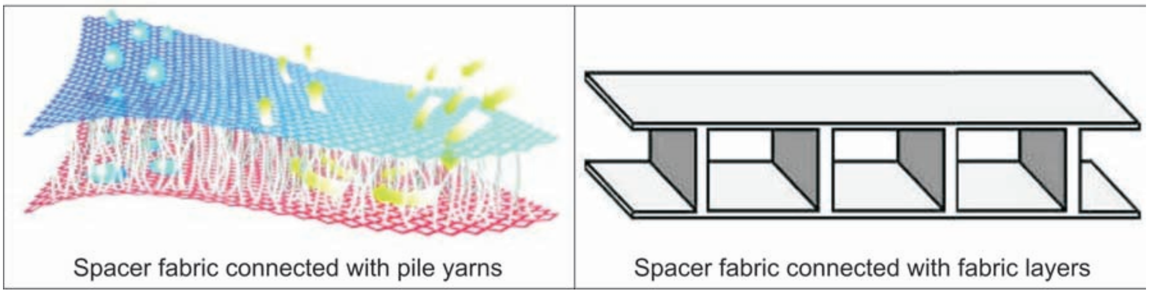


Figure 3.5: Schematic of spacer fabrics

3.3.1 Woven spacer fabrics

Weaving is well-known for flat and multi-layered fabrics, which can be woven using almost any type of yarn. The proportion of the yarns in the x-, y- and z-direction can be controlled to tailor the properties of end products. However, among all the distinguished woven structures, only the double-wall woven fabrics could be categorized as the woven spacer fabrics, since in double-wall weaving two surface fabrics are connected with pile yarns creating a hollow space between them. To produce double-wall fabric, two layers of fabrics are woven together with yarns binding them. These binding yarns could be cut to separate the layers resulting in a fluffy surface on one side of each fabric. The product features can be varied by means of four separate factors: the material, the fabric construction, the thread-linking system and the finish. The woven spacer fabrics, 3D fabrics and composites have been presented in Figure 3.6 [60–65].

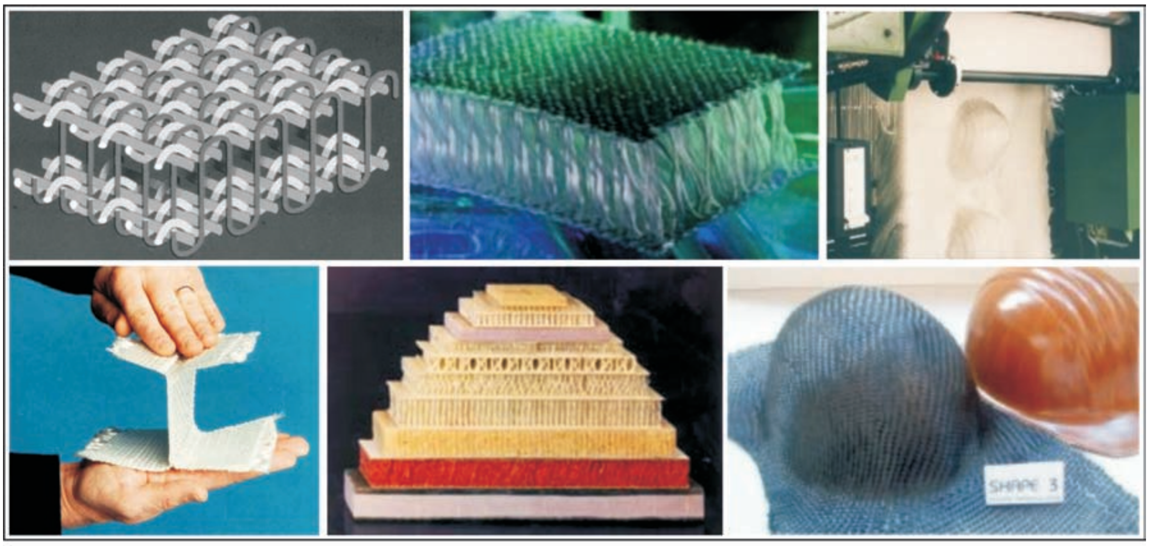


Figure 3.6: Example of 3D woven preforms and composites [60, 61, 63, 64]

Some development of woven spacer fabrics consisted with two surface fabrics and separate connecting fabrics disposed between them were documented recently in the collaborative research program "Textile-reinforced composite components for function-integrating multi-material design in complex lightweight applications" funded by the German Research Foundation (SFB 639) at the Technical University of Dresden [26]. The developed innovative woven spacer fabric structures comprise only the U- and V-shaped spacer fabrics. Nevertheless, the pressing drawbacks of woven spacer and 3D fabrics include the reproducibility, cost-effectiveness, flexibility in design changing, integration of functional-component, fiber damages by the interlacing of high performance yarns, realization of different geometries including variable and shaped surface fabrics, variable connecting lengths, variable forms, etc. [26, 60, 61].

3.3.2 Braided spacer fabrics

In braiding, three or more threads interlace with one another in a diagonal formation, producing flat, tubular or solid constructions. The major developments in 3D braiding over recent years have been driven by the superior manufacturing and mechanical properties of braided composites over traditional laminates. Braided fabrics can often be used directly as net-shape preforms with intricate geometries for composites. Consequently, 3D braiding is considered to be more promising for composite industries. However, one major limitation is that, most 3D braiding machines are only capable of producing narrow preforms and almost all 3D braiding machines are still under development. Moreover, 3D braiding machines have long set-up times and it is a slow and costly process. Furthermore, most of the braided axial tows are off-axis from the loading direction and are heavily crimped, which lead to the damages of high performance yarns. Beyond these technological limitations, which could be overcome by further researches, 3D braiding technology based on the recent developments possess great potential for the manufacturing of 3D complex shaped textile preforms to be used in high performance composite applications. Some of the examples of 3D braided textiles and composites have been shown in Figure 3.7 [26, 60–62, 66].

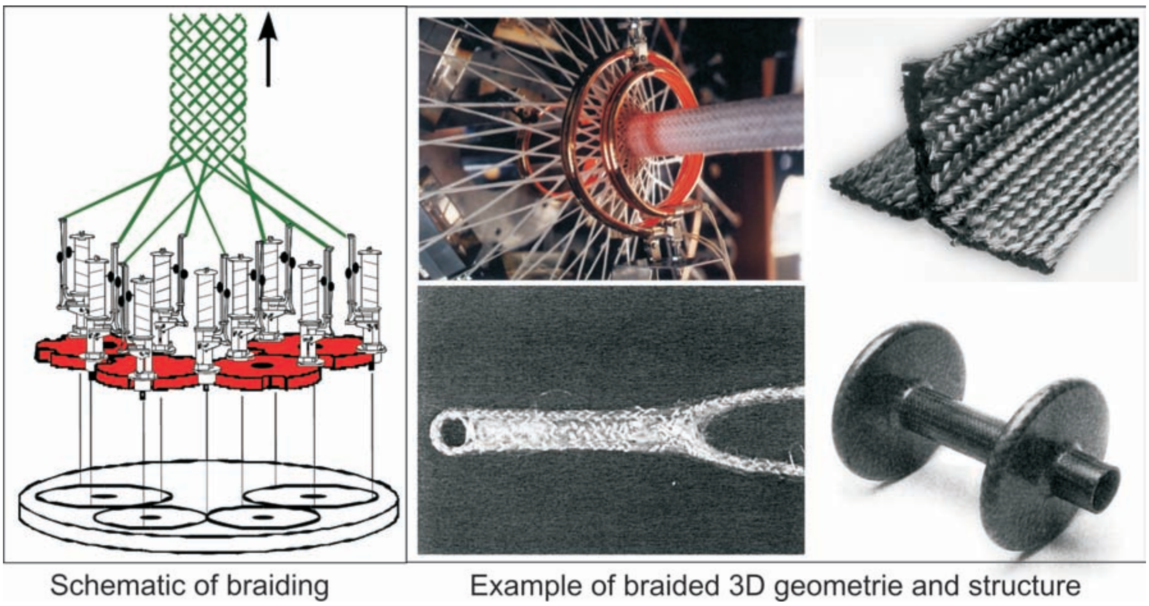


Figure 3.7: 3D braided textiles and composites [60, 61, 66]

3.3.3 Stitched spacer fabrics

Stitching is a process in which stitching threads are used to join fabric layers. Stitching is occasionally used in textile composites mainly to create 3D textiles by joining the multiple reinforcement fabric layers together and to improve the impact performance of composites. However, some latest technological advancement allow the manufacturing of complex shaped spacer fabrics [26], consisting of surface fabrics and connecting fabrics, by stitching technique which are produced using almost entirely flat textiles. Nevertheless, the distinguished disadvantages make the stitching technique not feasible for the preform manufacturing for composites. For example, the used sewing threads lead to in-homogeneity in the structure, which makes the composite structure weedy. Moreover, the multifaceted structures require complex robotically controlled multi-needle machines which are largely in the development stage and are expected to be very expensive for composite industries. Besides, the additional production stages raise the manufacturing cost of composites limiting suitable applications. Another predicament with current machineries is their difficulty in stitching large and thick structures [22, 26, 60–62].

3.3.4 Warp knitted spacer fabrics

Warp knitting is a family of knitting methods in which the yarns zigzag along the length of the fabric and follow the adjacent columns (wales) of knitting, rather than a single row (course). Warp knitting has inherited the ability to form stable fabric and since each needle has to be supplied with at least one yarn, a large number of yarn ends are required on a warp knitting machine. Currently, two types of 3D textiles could be produced by warp knitting, for example, non-crimp and sandwich 3D textiles. 3D warp knitted non-crimp preforms are produced following a combination of fiber tow placement and warp knitting, where the layers of unidirectional tows (non-crimp fabrics) are stacked in the required directions and then they are bound together with binder yarns inserted in the through-thickness direction by needles. On the other hand, sandwich 3D textiles, which are the conventional spacer fabrics, are produced on double-bed Raschel machines by knitting the top and bottom skins simultaneously on each needle beds. During the knitting process, yarns are intermittently swapped between two sets of needles to create a core of through-thickness yarns, called pile, which are interconnected to the skins. Figure 3.8 represents the warp knitted conventional spacer fabrics and the schematic of non-crimp 3D warp knitting. These conventional spacer fabrics are suitable for

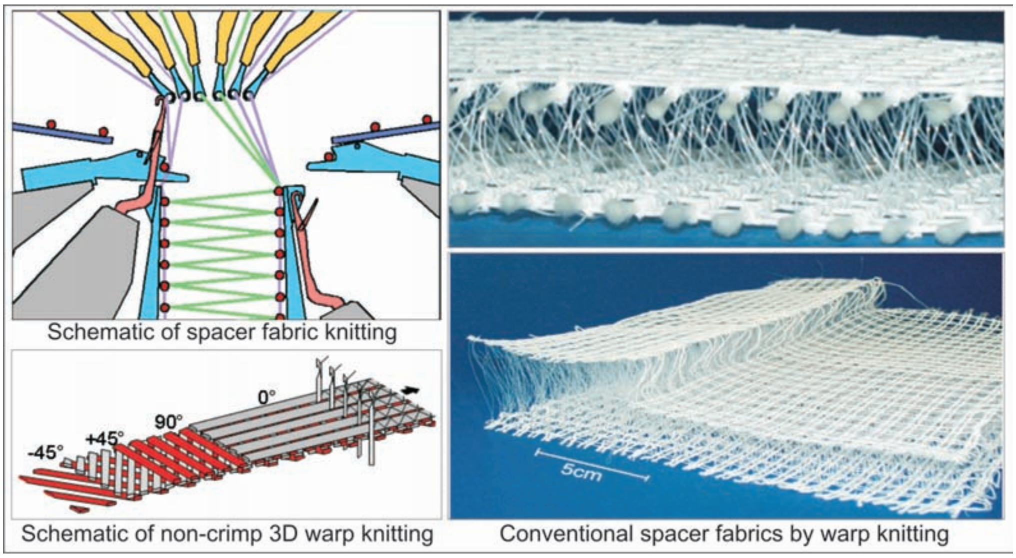


Figure 3.8: Warp knitted 3D preforms [61, 67, 68]

higher energy absorption and decorative purposes. But, the lower flexural stiffness, inferior specific compression strength, limited distance between the surface fabrics, lack of geometrical diversity along with inadequate reinforcement possibilities restraint the applications of this conventional spacer fabrics as 3D textile preforms in high performance composites [22, 30, 60–62, 67, 68].

3.3.5 Weft knitted spacer fabrics

3.3.5.1 Spacer fabrics by circular and flat knitting

Spacer fabrics consisting of two separate fabric layers connected vertically with pile yarns could be produced by weft knitting technique. On a double jersey circular knitting machine two surface layers could be knitted separately on both dial- and cylinder needle beds. Then the using of pile yarns could connect both surface layers by means of the tuck stitches alternatively on both needle beds to form conventional spacer fabrics. However, the inadequate distance between the surface fabrics along with the usage of relatively finer yarn constraint the application of such circular-knitted spacer fabrics. On the other hand, spacer fabrics with two surface layers connected with pile yarns could also be produced on V-bed flat knitting machine. Here it is again, both surface layers are knitted separately on both needle beds and then could be connected by the pile yarns as inclined or perpendicular. However, this technique puts forward a great variety of structures, combination of different yarn materials and even integration of reinforcing and functional components on both surface fabrics and as pile yarns. But, this technique is extremely limited due to the fixed needle beds of knitting machine, which causes the insufficient distance between the two surface layers produced on front and rear needle beds [30]. Moreover, elasticity and deformability due to applied forces, limited injections and lamination properties, worse flexural stiffness, lesser specific compression strength, lack of geometrical diversity along with inadequate reinforcement possibilities (e.g. in z-direction) limit the applications of these conventional spacer fabrics as 3D textile preforms in lightweight applications. The flat knitted conventional spacer fabrics are illustrated in Figure 3.9.

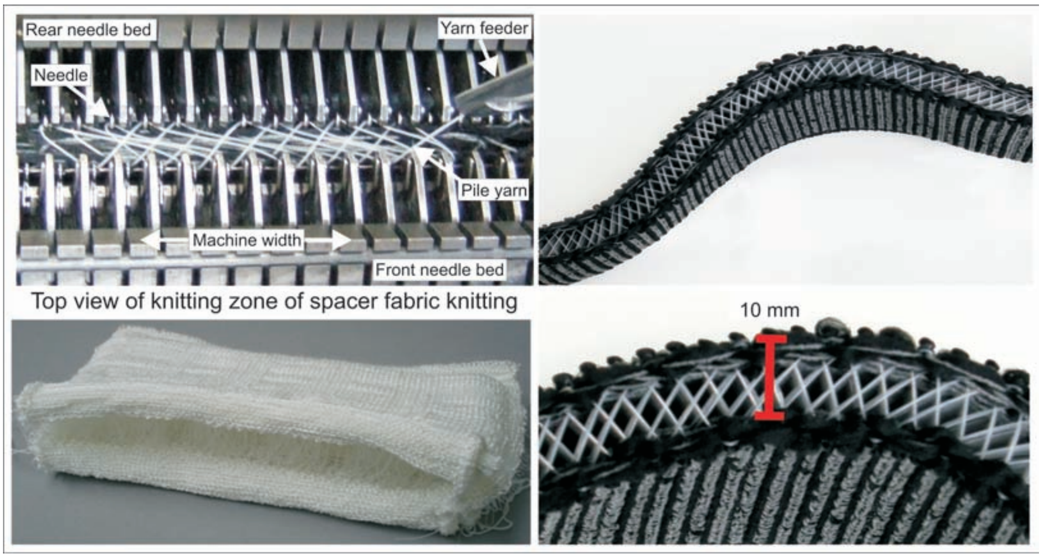


Figure 3.9: Flat knitted conventional spacer fabrics

3.3.5.2 Current research on the development of weft knitted spacer fabrics

The inventions of conventional spacer fabrics were documented by US patent no. 5735145 [69], 5284031 [70], 5422153 [71], 5395684 [72], 7611999B2 [73], to Pernick, Stoll et al., Miyamoto, Robinson et al., and McMurray respectively. These inventions claim the development of weft knitted spacer fabrics comprising of two parallel surface fabrics joined by pile yarns with combination of different yarn materials, diverse connecting techniques, various surface designs and the assorted end uses. It is also known by DE 4008057A1 [74] to produce two separate knitted webs on knitting machines simultaneously parallel to each other by means of two needle beds. A three-dimensional knitted structure can be made by interconnecting in different places of both knitted webs. The knitted webs can also be connected by a third knitted web without any reinforcement inlay threads according to DE 4008057A1. The invention of a multilayer knit especially for seat cover is known by DE 19855541A1 [75], in which the layers are knitted by knit loops and tuck stitches in different courses/ wales using variable yarn finenesses. A novel inlaid double needle bed fabric is documented by GB 2233989A [76]. Only the course directional inlay thread is interlaced into the fabric by transferring stitches from the active needles of one needle bed to the needles of other needle bed. According to DE 3643357A1 [77], the connection is made at least one knitted-in or inwrought, comparatively thin, separate intermediate thread or a knitted structure. With this kind of connection of two halves of knitted structure, the coherence is established by the formation of loops. The binding thread itself forms stitches or loops. DE-PS 458906 [78] reports a multilayer knitted structure comprising two plain knitted webs, in which their fabric-backs facing each other are being introduced by a third thread system consists of a bundle of standing threads by which the coherence of the outer knitted webs is ensured. The third thread system is intended to stuff the knitted structure better and to provide strength in the longitudinal direction. By DE 4419985C2 [79] and US 6244077B1 [80] the invention of multilayer knitted structures includes at least two knitted webs which are interconnected by a third thread system is known. The construction of such multilayer knitted structure is done by using the needles of both needle beds. However, the most of the reported spacer fabrics, documented by US patent no. 5735145 [69], 5284031 [70], 5422153 [71], 5395684 [72] and 7611999B2 [73], comprising with multi-layered surface layers are connected with pile yarns produced by knitting technology which are elastic in nature and dimensionally not stable under applied forces, whereas the fabric structures are not suitable to carry the applied forces in 3D directions. Additionally, the limited distance between the surface layers is also a drawback of such spacer fabrics. Moreover, the spacer fabrics documented by DE 4008057A1 [74], DE 19855541A1 [75], GB 2233989A [76], DE 3643357A1 [77], DE-PS 458906 [78] are not actually the 3D spacer structures, and these 3D geometries allow less possibilities to carry loads in 3D directions in high performance composite applications. By DE 4419985C2 [79] and US 6244077B1 [80] the invention of multi-layered knitted structures with semi-finished structures as well as with increased thickness by additional warp and weft threads is documented (Figure 3.10). However, the realization of a 3D spacer fabric structure is not possible by such invention.

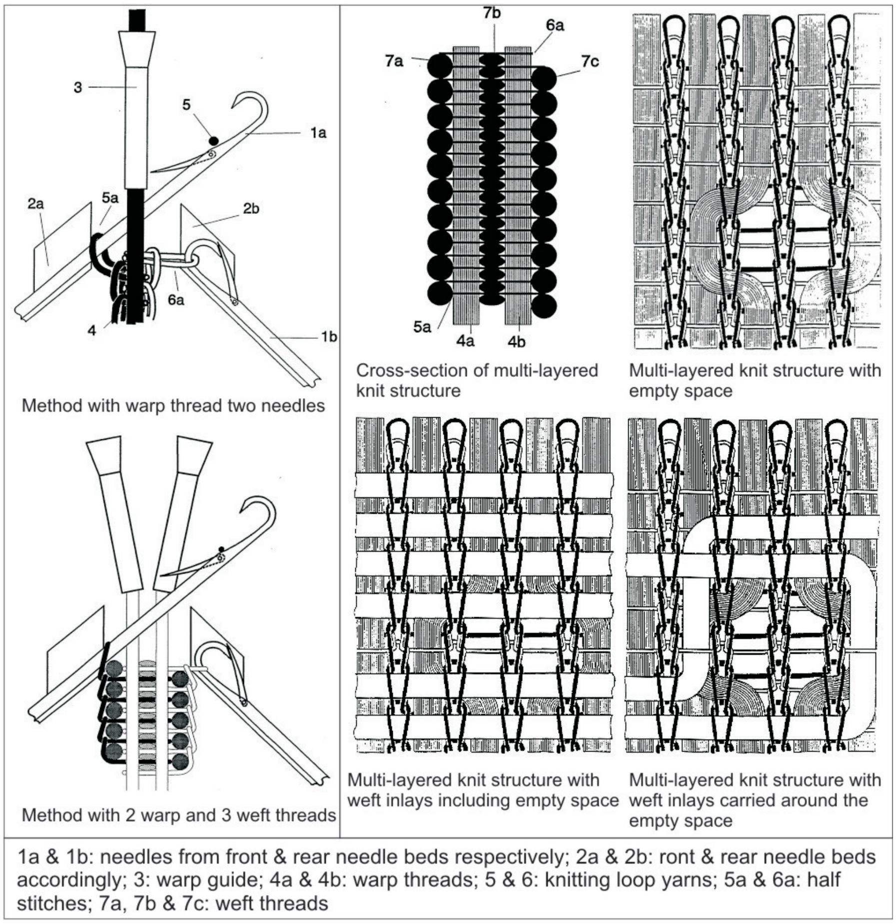


Figure 3.10: Innovative multi-layer knitting for semi-finished structures [79, 80]

On the other hand, few research works have been reported on the development of 3D spacer fabrics consisting of surface fabrics connected with fabric layers between the planes. Hong et al. [27] presented the basic production principles of some selected flat knitted spacer fabrics without any reinforcement (using only the mesh structures). Ciobanu [28] reported the theoretical presentation of knitted sandwich spacer fabrics including the current state of the knitted sandwich fabrics and the possible ways of development of complex shape structures. Conversely, these spacer fabrics do not meet the structural requirements for the application as reinforcement textile preforms in high performance composite applications. On the other hand, Araujo et al. [29] carried out the research in order to exploit the potentialities of electronic flat knitting machines in the production of weft knitted novel structures and they reported the analysis of spacer fabrics on the basis of surface and connecting layers.

3.3.6 Application of conventional spacer fabrics

The principal advantages of pile yarns connected conventional spacer fabrics are the breathability, energy absorption, compression strength, insulation, pressure redistribution, good dispersion of moisture, recyclability, etc. These advantages make the conventional spacer fabrics very suitable in diverse applications, such as, in the areas of automotive and other transportation media, medical, hygiene and healthcare, geotextiles, civil engineering, building and construction, sports and leisure, environmental protection, filtration, cleaning, safety and protection, decorative purposes, etc. In automotive industries, the conventional spacer fabrics are mostly used in seat cushions, head liners, luggage compartment covers, seat packets and dash boards, etc. [30, 67, 81]. Due to heat and moisture absorbing and transporting properties the conventional spacer fabrics are idle for use in medical textiles and being widely used as bandages for oedema treatment in case of chronic venous insufficiency and chronic lymphatic insufficiency, orthopaedic knee braces, as pressure sore prevention on beds in the operating theatre and for wheelchair patients, for prevention ulcers with diabetic foot syndrome, incontinence bed pads, etc. [82]. On the other hand, these spacer fabrics are being widely used in sports wears, where the moisture and temperature controls phenomenon along with the energy absorption concepts make the conventional spacer fabrics forerunner to do so. Again, such pile yarns connected spacer fabrics are showing rising demands in the area of civil engineering applications, such as, in erosion control, soil reinforcement, concrete reinforcement, separation, filtration, drainage, etc. However, conventional spacer fabrics are very common in the field of safety and protection, for instance, to protect against extreme heat and fire, harmful chemicals and gases, mechanical and electrical hazards, contamination, radiation, vacuum and pressure fluctuations, ballistic hazards, etc. [30]. Further promising application of these spacer fabrics using favourable materials include the protective textiles as "Active Protection System (APS)" [83]. Nevertheless, because of the extreme elasticity and deformability due to applied forces along with limited reinforcing possibilities, these pile yarns connected conventional spacer fabrics are not considered as load-adapted 3D spacer textile preforms for high performance lightweight composites applications.

3.4 Panel-structures in lightweight application

3.4.1 Conventional panel-structures

Panels are the rigid sandwich components which are widely used in lightweight applications. This sandwich construction provides a very lightweight structural configuration for complex load conditions. Conventional panels are mainly the metallic/ fiber-reinforced plastic surfaces bonded by adhesives with metallic/ polymeric honeycomb or foam cores. Many advantages of these panels include the greater specific stiffness, high strength to weight ratio, sound-deadening, vibration absorption, thermal insulation, impact absorption, buoyancy, etc. The face sheets take the membrane and bending loads while the core resists the shear loads. Such panel structures are being used in lightweight industries, especially in aircraft, aerospace vehicles, transport vehicles, marine vehicles, marine infrastructures, lift cabins, etc. For the fabrication of strong and stiff faces, the fiber reinforced composites or the thin metal sheets of Aluminium or conventional steels are used in industrial scales. Conversely, Aluminium honeycomb is widely used as the core in panel design to add bending stiffness with very little mass penalty. Alternatively, metallic and polymeric foams are also attractive structural materials as the core in panel construction. Some conventional panels of lightweight industries have been documented in Figure 3.11 [84–95].

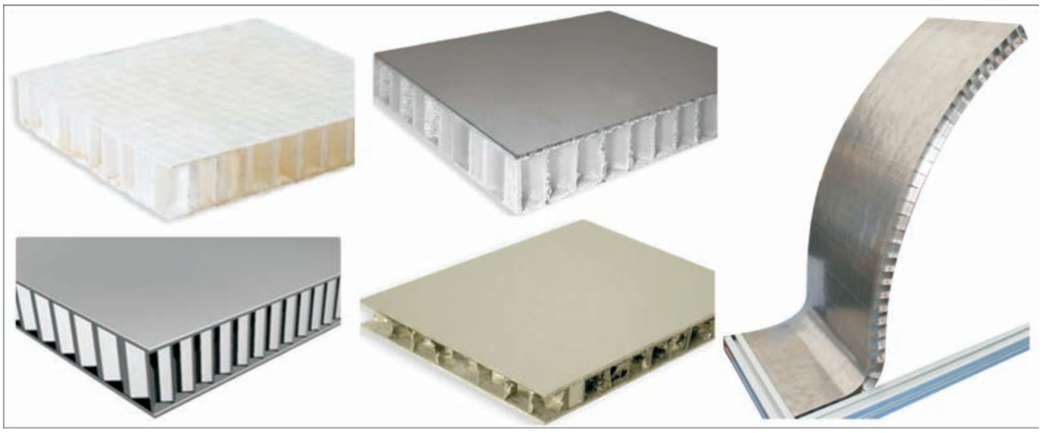


Figure 3.11: Example of conventional panels used in lightweight industries [96, 97]

With regardless of the mass-penalty, aluminium honeycomb sandwich panels are well-known for their high mechanical performances, especially for the ultimate strength in axial tension & compression as well as for the bending stiffness & rigidity. However, in order to realize these mechanical performances more elaborately, the theoretical strength characteristics of aluminium honeycomb sandwich panels are discussed in the next subsection.

3.4.2 Strength characteristics of aluminium honeycomb sandwich panels

Since the aluminium honeycomb (sandwich) panels are recognized as very promising structural design systems for lightweight applications, the theoretical and practical investigations on the strength characteristics of such panels have been followed by many researchers [98–103]. Before theoretical discussion on the strength characteristics, the basic structural properties of aluminium honeycomb panels should be defined first. Figure 3.12 (a) shows the schematic of common aluminium honeycomb-cored sandwich panel.

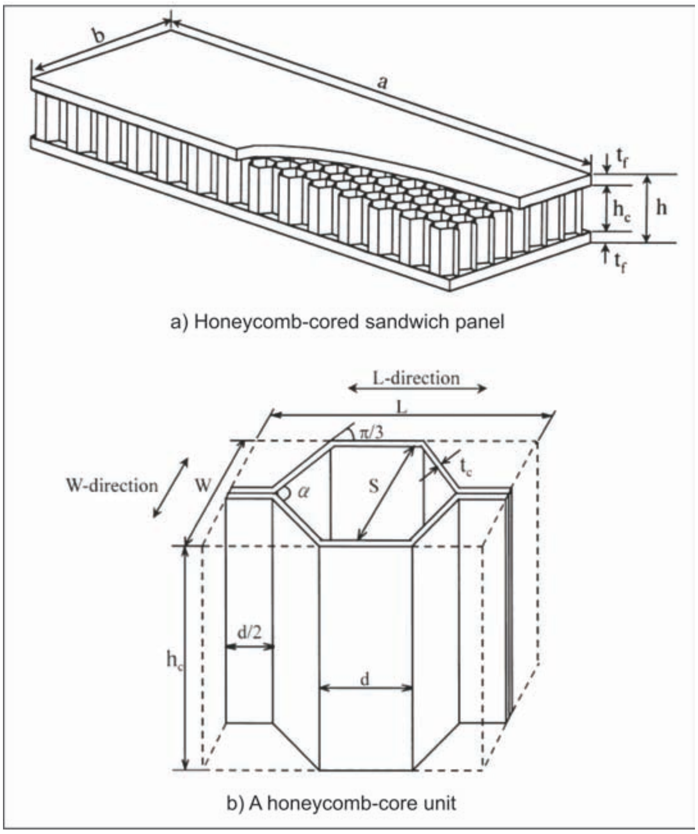


Figure 3.12: Honeycomb-cored sandwich panel (a) and a honeycomb-core unit (b) [100]

For the simplicity, the facings are assumed to have equal thickness t_f, and the core height is denoted h_c. Figure 3.12 (b) shows one unit of the honeycomb core. In Figure 3.12, the L and W directions are taken in the directions parallel and normal to corrugation, respectively [100].

The facing skins of a sandwich panel can be regarded as the flanges of an I-beam, since they carry the bending stresses to which the panel is subjected with one facing skin in compression, and the other in tension. Similarly, the core corresponds to the web of the I-beam. It is assumed that the core carries no longitudinal stress and resists the shear forces. The core holds the facing skins apart such that the stiffness of the structure is increased. A core to skin joint rigidly joins the sandwich components and allows them to act as one unit with high torsional and bending rigidity. The moment of inertia of the facing skins for a honeycomb sandwich panel can be calculated by [100]:

$$I_f = \frac{\left(h^3 - h_c^3\right)}{12} \cdot b \tag{3.1}$$

Where, I_f is the moment of inertia of facing skins of honeycomb sandwich panel, h is the height of sandwich panel including both facing skins, h_c is the height of honeycomb core, b is the breadth of the sandwich panel or beam. The virtual area of a unit honeycomb core at the cross section parallel to the facing skin plane is given by [100]:

$$A = L \cdot W \tag{3.2}$$

Where, A is the virtual area of a unit honeycomb core at the cross section parallel to the facing skin plane, L and W are the length and width of single honeycomb-core unit respectively. One major reason why aluminium honeycomb sandwich panels are of interest is due to their lightweight characteristics. Therefore, it is of crucial importance to accurately predict the weight of aluminium honeycomb sandwich panels so that performance measures for sandwich construction, e.g., strength to weight ratio, can be correctly computed. The mass of the aluminium honeycomb sandwich panel can be estimated from [100]:

$$m = m_f + m_c \tag{3.3}$$

Where, m is the total mass of the honeycomb sandwich panel, m_f and m_c are the mass of facing materials and honeycomb core accordingly. By neglecting the contribution of materials used for joining honeycomb core cells, such as adhesives, to the total weight of honeycomb cores, the average density of honeycomb cores can be obtained from [100]:

$$\rho_{ca} = \frac{8 \cdot d \cdot t_c}{A} \cdot \rho_c \cong \frac{8}{3\sqrt{3}} \cdot \frac{t_c}{d} \cdot \rho_c \tag{3.4}$$

Where, ρ_{ca} is the average density of honeycomb cores over an entire sandwich panel, d is the breadth of one edge of honeycomb core cell, t_c is the wall thickness of honeycomb core cell, ρ_c is the density of honeycomb core material (aluminium alloys). Equation (3.4) indicates that the average core density is expressed in terms of wall thickness and edge breadth of honeycomb core as well as the material density itself. Thus, ρ_{ca} can be used as a useful parameter in representing the strength properties of a honeycomb core.

3.4.2.1 Ultimate compressive strength of alumunium honeycomb panels

In order to calculate the ultimate strength for honeycomb sandwich panels under axial compression an equivalent single plate approach, in which the honeycomb sandwich panel is replaced by an equivalent single skin panel in the strength calculation, is employed. Figure 3.13 represents a schematic concept of the equivalent single skin approach [100].

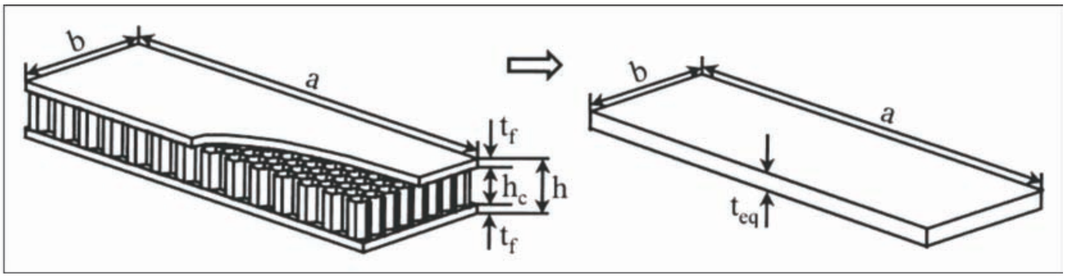


Figure 3.13: A schematic of the equivalent single skin approach [100]

To replace the honeycomb sandwich panel by the equivalent single skin plate, two methods, namely the equivalent rigidity method and the equivalent weight method, may be considered. In the equivalent rigidity method, plate thickness and elastic modulus are defined such that the rigidity of the sandwich panel is equivalent to that of the single skin panel. In the equivalent weight method, dimensions of the equivalent single skin panel are defined so that the structural weight is equal. The equivalent material properties of the single skin panel with the equivalent rigidity can be estimated from the following equations [100, 101]. The rigidity of the panel with equal facing skin thickness is considered separately for in-plane tension, bending and shear:

In tension:

$$2 \cdot t_f \cdot E_f = t_{eq} \cdot E_{eq} \tag{3.5}$$

In bending:

$$\frac{1}{12}[(h_c + 2t_f)^3 - h_c^3]E_f = \frac{1}{12} \cdot t_{eq}^3 \cdot E_{eq} \tag{3.6}$$

In shear:

$$2 \cdot t_f \cdot G_f = t_{eq} \cdot G_{eq} \tag{3.7}$$

Where, t_f is the thickness of facing skin (assuming that both skins are of same each other), t_{eq} is the equivalent thickness, E_f is the elastic modulus of the facing material, E_{eq} is the equivalent elastic modulus, G_f is the shear modulus of facing skin, G_{eq} is the equivalent shear modulus. The values t_{eq}, E_{eq} and G_{eq} could be calculated as follows [100, 101]:

$$t_{eq} = \sqrt{(3 \cdot h_c^2 + 6 \cdot h_c \cdot t_f + 4 \cdot t_f^2)} \tag{3.8}$$

$$E_{eq} = \frac{2 \cdot t_f \cdot E_f}{t_{eq}} \tag{3.9}$$

$$G_{eq} = \frac{2 \cdot t_f \cdot G_f}{t_{eq}} \tag{3.10}$$

On the other hand, the equivalent plate thickness t_{eq} of the single skin plate based on equal weight may be calculated from [100, 101]:

$$L \cdot W \cdot t_{eq} \cdot \rho_f = L \cdot W \cdot 2 \cdot t_f \cdot \rho_f + L \cdot W \cdot h_c \cdot \rho_{ca} \tag{3.11}$$

resulting in

$$t_{eq} = \frac{2 \cdot t_f \cdot \rho_f + h_c \cdot \rho_{ca}}{\rho_f} \tag{3.12}$$

Where, ρ_f is the density of facing material (aluminium alloys). The elastic and shear modulus of the equivalent single skin panel are assumed to equal those of facing skin materials [100, 101], namely

$$E_{eq} = E_f, G_{eq} = G_f \tag{3.13}$$

In this study, a form of the Frankland equation is used to predict the ultimate strength of the aluminium sandwich panel under uni-axial compression together with the apparent thickness and modulus as obtained above. Thus it could be formulated [100, 101]:

If β is equal or smaller than 1, then

$$\frac{\sigma_u}{\sigma_{fo}} = \frac{a_1}{\beta} - \frac{a_2^2}{\beta^2} \tag{3.14}$$

Again, if β is greater than 1, then

$$\frac{\sigma_u}{\sigma_{fo}} = 1.0 \tag{3.15}$$

The value of β could be calculated by

$$\beta = \frac{b}{t_{eq}}\sqrt{\frac{\sigma_{fo}}{E_{eq}}} \tag{3.16}$$

Where, σ_u is the ultimate strength of the sandwich panel in axial compression, σ_{fo} is the yield stress of facing material. a_1 and a_2 are the constants depending on the plate boundary conditions. Faulkner [102] proposes a_1 = 2.0, a_2 = 1.0 for simply supported plates and a_1 = 2.25, a_2 = 1.25 for clamped plates.

3.4.2.2 Flexural behaviours of alumunium honeycomb panels

The aluminium honeycomb-panels are renowned for their improved flexural behaviours. The flexural properties of sandwich structures are usually affected by facing and core materials, where the properties of core materials effect mostly on deformation and strength of panel with different dimension. In order to determine the panel bending stiffness and rigidity, core shear stress and modulus, facing bending stress the following equations are applied based on short beam and long beam loading method as

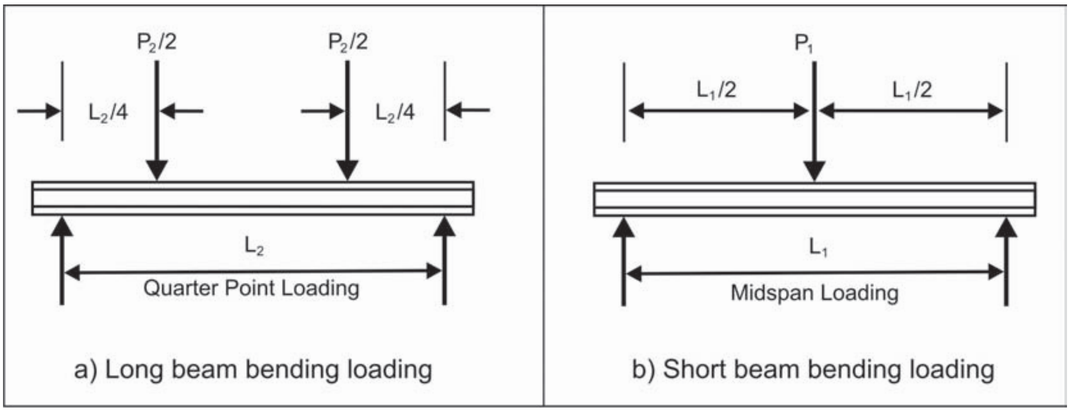


Figure 3.14: Long and short beam loading (flexural) of panels [103, 104]

illustrated in Figure 3.14, which is used in the standard method ASTM C-393 [103, 104].

$$\tau_c = \frac{P_1}{(d+c) \cdot b} \tag{3.17}$$

$$\sigma_f = \frac{P_2 \cdot L_2}{4t \cdot (d+c) \cdot b} \tag{3.18}$$

$$\Delta_1 = \frac{P_1 \cdot L_1^3}{48D} + \frac{P_1 \cdot L_1}{4U} \tag{3.19}$$

$$\Delta_2 = \frac{11 \cdot P_2 \cdot L_2^3}{768D} + \frac{P_2 \cdot L_2}{8U} \tag{3.20}$$

$$D = \frac{P_1 \cdot L_1^3[1 - (11 \cdot L_2^2/8L_1^2)]}{48 \cdot \Delta_1[1 - (2 \cdot P_1 \cdot L_1 \cdot \Delta_2/P_2 \cdot L_2 \cdot \Delta_1)]} \tag{3.21}$$

$$G = \frac{P_1 \cdot L_1 \cdot c[8 \cdot L_1^2/11L_2^2 - 1]}{\Delta_1 \cdot b(d+c)^2[(16 \cdot P_1 \cdot L_1^3 \cdot \Delta_2/11 \cdot P_2 \cdot L_2^3 \cdot \Delta_1) - 1]} \tag{3.22}$$

$$D = \frac{E_f \cdot b(d^3 - c^3)}{2} \tag{3.23}$$

$$U = \frac{G(d+c)^2 \cdot b}{4c} \tag{3.24}$$

Where, τ_c is the core shear stress (MPa), P_1 is the short beam load (N), P_2 is the long beam load (N), d is the sandwich thickness (mm), c is the core thickness (mm), b is the sandwich width (mm), σ_f is the facing bending stress (MPa), t is the facing thickness (mm), L_1 is the short beam span length (mm), L_2 is the long beam span length (mm), U is the panel shear rigidity (N), E_f is the facing modulus (Mpa), D is the panel bending stiffness ($N - mm^2$), G is the core shear modulus (MPa) and Δ_1 & Δ_2 are the total beam midspan deflections (mm).

The aluminum honeycomb sandwich panels, because of their superior mechanical and structural properties, are very renowned as conventional panels for structural designs in lightweight applications. Nevertheless, such structures are to be blamed for various inconveniences in applications. One major disadvantage of these honeycomb sandwich panels is their excessive weight due to solid-metal structures. One innovative solution is to design textile reinforced composite panels along with the hollow spaces within the structures leading to reduced weight including the possibilities of diverse-usage of hollow space. Nonetheless, the major disadvantages of conventional panels are discussed in the following sections.

3.4.3 Disadvantages of conventional panel-structures

While metal-based conventional sandwich panels are widely used in lightweight industries, however, remarkable drawbacks are also claimed for these panel structures in applications. First of all, the excessive weight of the metal-based panel causes to higher fuel consumption for the transport vehicles. In addition, the adhesive bonded panels are less efficient while experienced with loads, especially in transverse direction of the binding. Moreover, laminated stiffened panels are non-homogeneous and anisotropic in nature. Metal steel structures are prone to suffer various types of defects such as corrosion, cracks, and dents. Also, it is difficult to utilize other than flat structures. Besides, the manufacturing of such sandwich panels is extremely slow process and executed mostly through handworked methods. Consequently, the cost of the panels is considered to be excessive for transport industries. On the other hand, foam core-based panels are not suitable as high performance components for their inferior mechanical properties (especially in z-direction), since there is little room for improving mechanical properties in foaming process (metallic and polymeric) by adding alloying elements or dispersing strengthening particles because of their narrow foaming and solidification conditions. Likewise, the large pore size and an inhomogeneous pore distribution often decrease the mechanical properties. Furthermore, the polymeric core-foams release toxic fumes when they are processed. Besides, the realization of complex-shaped structures with flexible structural diversities is not feasible by the conventional panel manufacturing techniques [84–103].

3.4.4 Comparison of textile technologies for the manufacturing of 3D textile preforms for panel-structures

The discussion on the spacer fabrics by different textile technologies stated in section 3.3 provides the present technological advancements for the manufacturing of 3D textile preforms for composites. Principally, most of the textile technologies could be used to manufacture universal 2D textiles. Semi-finished 2D textile preforms developed for high performance composites, which are produced with multi-layered reinforcements in x- and y-directions, can also be reinforced in the z-direction along with the variable geometries (including hollow shapes) by the recent developments of textile technologies. Again, innovative multi-layered 3D textiles, for example, 3D spacer fabrics could be potentially used as textile preforms in the manufacturing of lightweight structures, for instance, for panel-structures, if such novel spacer fabrics could be manufactured cost-effectively using high performance yarns. However, most of the textile technologies of 3D preforming are not considered to be feasible in industrial applications. The major drawbacks are the lack of technological advancements, inadequate processe-flexibilities, difficulties in the usage of high performance materials, damages of reinforcement yarns by manufacturing processes, higher investment costs, limitations on medium to large scale productions, etc. Nevertheless, a short comparison of main textile technologies for 3D textile preforms is presented in Tables 3.3, 3.4 and 3.5.

Technology	**Advantage**	**Limitation**	**Investment cost**
Flat weaving	flexible for different materials, high productivity	Only 2D textiles, interlacement of warp and weft yarns	High
3D weaving: conventional spacer fabric	Planes connected with pile yarns, flexible for different materials	Less rigidity, limited distance between the planes, not suitable for composites	Very high
3D weaving: innovative spacer fabric	Planes connected with fabric layers, suitable for 3D composites	Not flexible system, damages of fibers by interlacement, complex set-up	Machine in development

Table 3.3: Comparison of textile technologies for 3D textile preforms [22, 26, 60–63]

Technology	**Advantage**	**Limitation**	**Investment cost**
3D weaving: Shape 3	3D reinforced structures	Reinforcements are only in x- und y- directions, dummy take off necessary, no undercuts realizable, fiber-damages by interlacement	Machine in development
3D weaving: 3tex	3D reinforced structures	Only profiles with constant cross section, fiber-damages by interlacement, less productivity	Machine in development
Braiding	3D reinforced structures, various geometries, fibers orientation from 30° to 60°	Less flexibility, less productivity, fiber-damages by interlacement	Very high
Warp knitting: conventional spacer fabric	Planes connected with pile yarns, flexible for different materials	Less rigidity, limited distance between the planes, not suitable for composites	Very high
Warp knitting: 3D non-crimp textiles	Non-crimp yarns arranged in multiple layers in multiple directions (in xy-plane)	Not 3D hollow structures, not flexible in form-ability, no reinforcement in z-direction	Very high
Stitching	Non-crimped yarns in multiple layers in multiple directions	Limited drapability, asymmetric layers, filament damage, less flexibility, no reinforcement in z-direction, not homogeneous structure	Very high
Non-woven	Starting from discontinuous fibers to fabric, quick process	No non-crimp arrangement of fibers, poor mechanical properties, lack of mechanical cohesion, less rigidity	Very high

Table 3.4: Comparison of textile technologies for 3D textile preforms [22, 26, 30, 60–68]

Technology	Advantage	Limitation	Investment cost
Circular knitting (weft): conventional spacer fabric	Planes connected with pile yarns, flexible for different materials	Less rigidity, limited distance between the planes, not suitable for composites, limited yarn fineness	High
Flat knitting (weft): conventional spacer fabric	Planes connected with pile yarns, flexible for different materials	Less rigidity, limited distance between the planes, not suitable for composites	High
Flat knitting (weft): 3D fabric	Very good drapability, multi-layered non-crimp yarns in 0° & 90° directions, near net shaping, flexible process, cost-effective, less wastage, high potentiality of further developments (e.g. innovative 3D spacer fabrics), less investment cost	Only in research scale realised, no reinforcement in z-direction, only weft and warp inlays	Machine in development

Table 3.5: Comparison of textile technologies for 3D textile preforms [22, 26, 30, 60–62]

According to the comparison of textile technologies presented in Tables 3.3, 3.4 and 3.5, the flat knitting is considered to be most competitive solution for the development of innovative near to net shaped 3D textile preforms for high performance composites. Because of the ground-breaking innovative technological features, the modern flat knitting machines show strong potential for the development and manufacturing of novel 3D textile preforms for lightweight panel-structures leading to the advantages like the cost effective flexible manufacturing, usage of the high performance fibers, non-crimped multi-layered arrangement of yarns, less wastage, improved mechanical properties for the composites (high loading, stiffness, energy absorption), flexibility in the diversifications of 3D geometries, etc.

3.4.5 Potential panel-structures on the basis of textile composites using innovative 3D spacer fabrics

High performance fiber-reinforced composites are the lightest weight-material systems due to their excellent specific stiffness. In comparison to the conventional metal designs, fiber reinforced composites have the advantages like substantially lower weight, arrangement of fibers to the load directions, extremely small co-efficient of thermal expansion, better fire resistance, low manufacturing cost, better weapon/ ballistic protections, high fracture toughness, easy recycling, short processing time, various forming possibilities, weld-ability, resistance to medias and corrosion, etc. [12, 13, 26, 84–95]. Therefore, a sandwich panel employing fibre-reinforced composite materials as plane layers connected with the same brings together the excellence of both the structural configuration and materials systems. Consequently, the innovative multi-layer reinforced 3D spacer fabrics produced in single stage manufacturing-process show great potential as textile preforms for high performance composites to substitute the conventional metal based panel structures in lightweight applications. Additional opportunities are the usage of the channels as fuel or Hydrogen/ Oxygen tank or for the sound damping materials. The bag chambers could also be used to accommodate the functional devices or various equipments [12,13,26]. The Figure 3.15 shows the possible promising application areas of composite panel-structures based on 3D spacer fabrics.

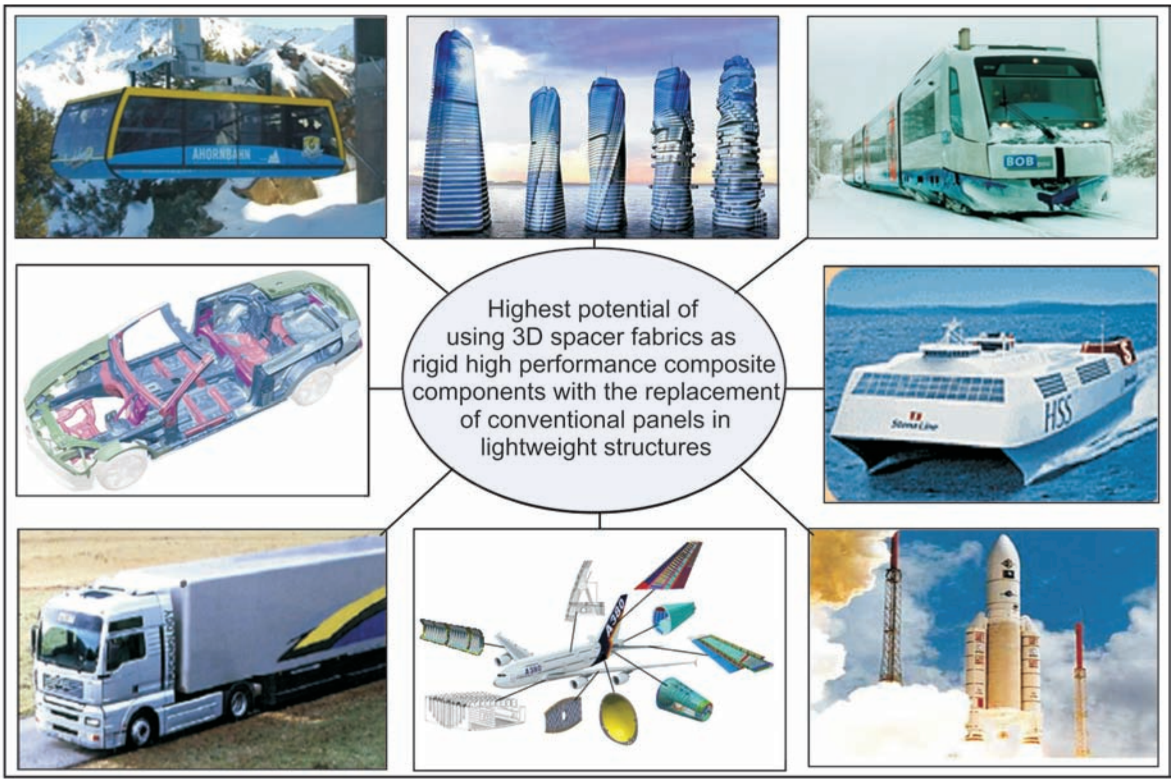


Figure 3.15: Potential application areas of 3D spacer fabrics as composite panels [105–110]

Chapter 4

Objective of the Research

The description of the function of the automatic power flat knitting machine discussed in the chapter 2 reveals that such flat knitting technology, because of its modern features and flexible manufacturing process, can be used also for the development and manufacturing of innovative technical textiles, especially complex "near to net" shaped textile preforms for composites. The state of the art discussed in the chapter 3 divulges that innovative multi-layer reinforced 3D spacer fabrics, which are consisted of plane layers connected with individual fabric layers, show great potential as textile preforms for high performance composites, if they could be produced cost-effectively through single stage manufacturing using high performance yarns. However, the conventional manufacturing techniques for 3D textile preforms (e.g. weaving, braiding, warp knitting, stitching), because of their technological limitation and lack of flexible-manufacturing processes, are not considered to be feasible for the development of innovative 3D spacer fabrics with multi-layer reinforcements. Nevertheless, the automatic power flat knitting machine could be a competitive alternative to develop these innovative multi-layer reinforced 3D spacer fabrics leading to niche applications in lightweight composite structures. Moreover, the development of thermoplastic composites from these flat knitted innovative 3D spacer fabrics using hybrid yarns, which are consisting of high performance and thermoplastic matrix materials, would be the breakthrough advancement for the composite manufacturers leading to surmount the diverse inconveniences caused by thermoset composites. These complex shaped thermoplastic composites could be the competitive solution to replace the conventional metal based panel structures in lightweight applications. However, for the engineering construction of flat knitted 3D spacer fabrics suitable for proper multi-directional reinforcement effects ("form follows force") for lightweight composites, it is indispensable to examine the compatibility of the usage of high performance yarns in knitting, the diversification of the geometries of 3D spacer fabrics, the methods of integration of reinforcement and functional yarns into 3D spacer fabric structures and the ultimate mechanical performances of thermoplastic composites on the basis of developed 3D spacer fabrics. In this backdrop, the main objectives of this research are:

- Development of flat knitting technology and manufacturing process for innovative 3D spacer fabrics consisting of individual surface and connecting layers
- Efficient usage of high performance yarns in flat knitting
- Innovative design of 3D spacer fabrics for high structural performances ("form follows force")
- Integration of reinforcement yarns into multiple layers in 3D spacer fabric structures for high mechanical performance
- Multi-layer construction of 3D spacer fabrics
- Creation of "sensor-network" (integration of functional yarn) into 3D spacer fabrics for structural health monitoring

- Fully-automated single-stage manufacturing of flat knitted 3D spacer fabrics including all integrated functions
- Analysis, calculation and modeling of the mechanical performances of yarns, fabrics and composites

Chapter 5

Development of flat knitting technology for 3D spacer fabrics

5.1 Selection of flat knitting machines

5.1.1 Required technical features

For the development of complex shaped 3D spacer fabrics eligible for proper reinforcement effects in high performance composites, the integration of reinforcement warp and weft yarns as multiple layers along with the engineering construction of 3D spacer fabrics are inevitable. However, in order to develop such spacer fabrics by flat knitting, following technical features of flat knitting machines should be considered first:

- Individual needle selection capability
- Loop transfer
- Fully-fashion technique
- Flexible and variable takedown system
- Adequate yarn feeders for weft and loop yarns

- Intermediate controlling system
- The usage of intarsia yarn feeders (for example, for the integration of sensor-network)
- Open carriage for integrating of at least two warp sets from above
- Spaces at the knitting zone for at least two warp and two weft systems along with two loop systems (for multi-layer reinforcements in order to increase the fabric specific weight)
- Modern patterning possibilities (e.g. CAD)

5.1.2 Technology-comparison of flat knitting machines

In order to categorize the flat knitting machines suitable for the development of 3D spacer fabrics, the main technical features of all available flat knitting machines at Institute of Textile Machinery and High Performance Material Technology (ITM) of Technical University of Dresden (TU Dresden) have been documented in Table 5.1. Hence, considering the available technical features presented in Table 5.1, the flat knitting machine CMS 320TC of company H. Stoll GmbH & Co. KG, Reutlingen of Germany [48] is selected for the development of spacer fabrics with different geometrical forms including course directional reinforcements. On the other hand, the flat knitting machines Aries.3 (1^{st} version: conventional & 2^{nd} version: advanced) of company Steiger SA of Switzerland [111] are selected for the development of multi-layer reinforced (as warp and weft inlays) 3D spacer fabrics. Figure 5.1 represents both flat knitting machines before any modification. However, the technical details and present status of these machines are presented briefly in the following sections.

Technical features	Stoll		Steiger Aries.3	
	CMT 211	CMS 320TC	Conventional	Advanced
Individual needle selection	-	X	X	X
Loop transfer	X	X	X	X
Holding down sinkers	-	X	-	-
Fully-fashion technique	-	X	X	X
Open carriage	X[a]	X[a]	X	X
Intermediate take-down	X	X	X	X
Main take-down	X	X	X	X
Take-down comb for start of fabric	-	X	-	-
Distance between needle beds	X[b]	X[c]	X[c]	X[b]
Yarn feeder selectors mounted on the carriage (not flexible system)	-	X	-	-
Special yarn feeder for weft yarn	-	-	X	X
Possibility of weft integration	X[d]	X[d]	X	X
Possibility of warp integration	X[e]	X[f]	X	X
Warp integration from above	X[g]	X[g]	X	X
Space for warp and weft yarn guides or feeders	X[h]	X[i]	X[j]	X[k]
CAD-Pattern system	-	X	X	X

Table 5.1: Technology-comparision of flat knitting machines at ITM, TU Dresden

In Table 5.1, a: modified at ITM; b: 10 mm; c: 5 mm; d: using normal yarn feeder; e: up to 4 warp sets, f: only 1 warp set; g: throw modified carriage; h: maximum 4 warp and 5 weft systems; i: maximum 1 warp and 1 weft systems; j: possibility of up to 2 warp and 2 weft systems; k: possibility of up to 5 warp and 6 weft systems.

Figure 5.1: Flat knitting machine: Stoll CMS 320TC [48] & Steiger Aries.3 [111]

5.1.3 Flat knitting machine: Stoll CMS 320TC

The CMS 320TC flat knitting machine is equipped with modern fully-fashioning technique. This machine is renowned for manufacturing of 2D or 3D "near to net" shape knitted structures. The CAD-patterning, loop transfer, individual needle selection capability, the usage of intarsia yarn feeders together with the presence of holding down sinkers are the epic features of this machine, which make it very effective for the development of innovative 3D spacer fabrics. However, this flat knitting machine has already been modified previously in some research projects at ITM, TU Dresden, especially for the development of biaxial reinforced textile preforms for composites [43]. The major modifications are, for example, the partition of carriage for integrating of single set warp yarns to the front needle bed, warp guides, advance creeling system of warp-spools, modified yarn feeders for weft and loop yarns. Nevertheless, the major technologies of this flat knitting machine are discussed briefly in the following subsections.

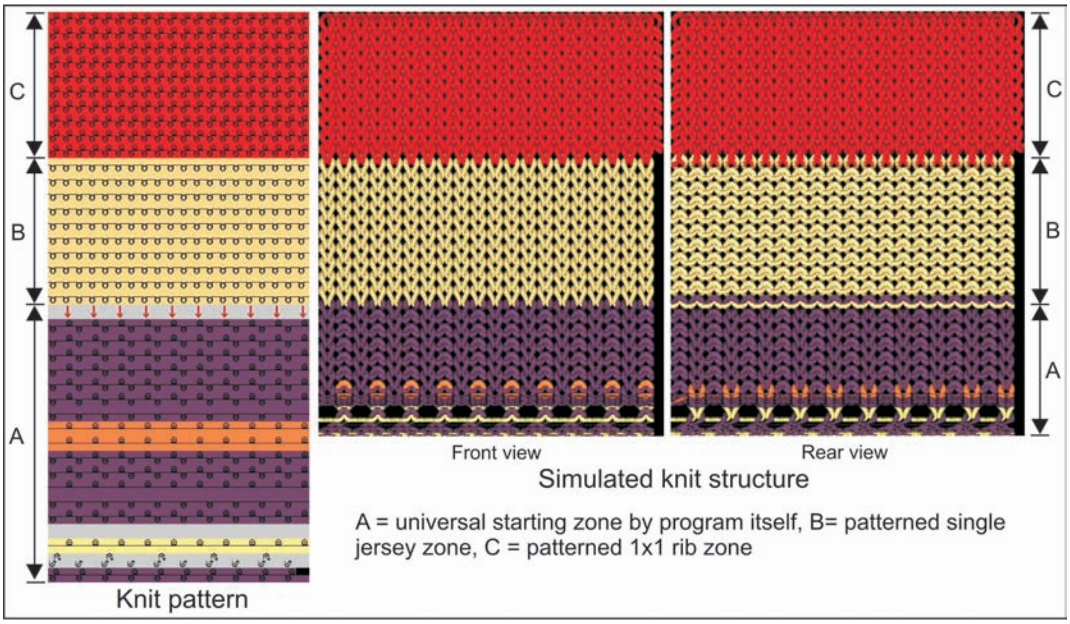


Figure 5.2: Example of knit pattern and simulated knit structure by M1plus CAD-system

5.1.3.1 CAD-patterning software: SIRIX & M1plus

Stoll CMS 320TC flat knitting machine supports the modern CAD-patterning software SIRIX, M1 and M1plus. However, M1plus is the latest version of CAD-patterning software of company Stoll and offers the knitting process in following main areas: design software, connectivity, machine management tools, machine operating system, etc. Moreover, M1plus offers colour arrangements and module arrangements windows with which it is possible to specify the knitting cycles graphically in a flexible way. For easy drawing of the pattern, without the influence of knitting technique aspects, it has the design mode. However, 3D spacer fabrics with and without course directional reinforcements including different geometries are developed in this research using both SIRIX and M1plus softwares. The Figure 5.2 shows an example of single jersey and 1x1 rib structures displayed by M1plus CAD-system.

5.1.3.2 Carriage

Carriage is the main operating system to perform the required function for generating of knitted fabrics. Carriage has three major parts: two different cam-box systems placed on both needle beds and yarn feeder selection unit above the yarn feeder rail. The yarn feeder selection unit is joined with both cam-box systems with bows and make the assembly into one rigid unit, which is driven by the motor-operated belts to traverse over the needle beds and yarn feeder rail. This carriage has previously been divided especially at yarn feeder selection unit to integrate single set of warp yarns to the front needle bed for multi-layer knitting [43]. However, each com-

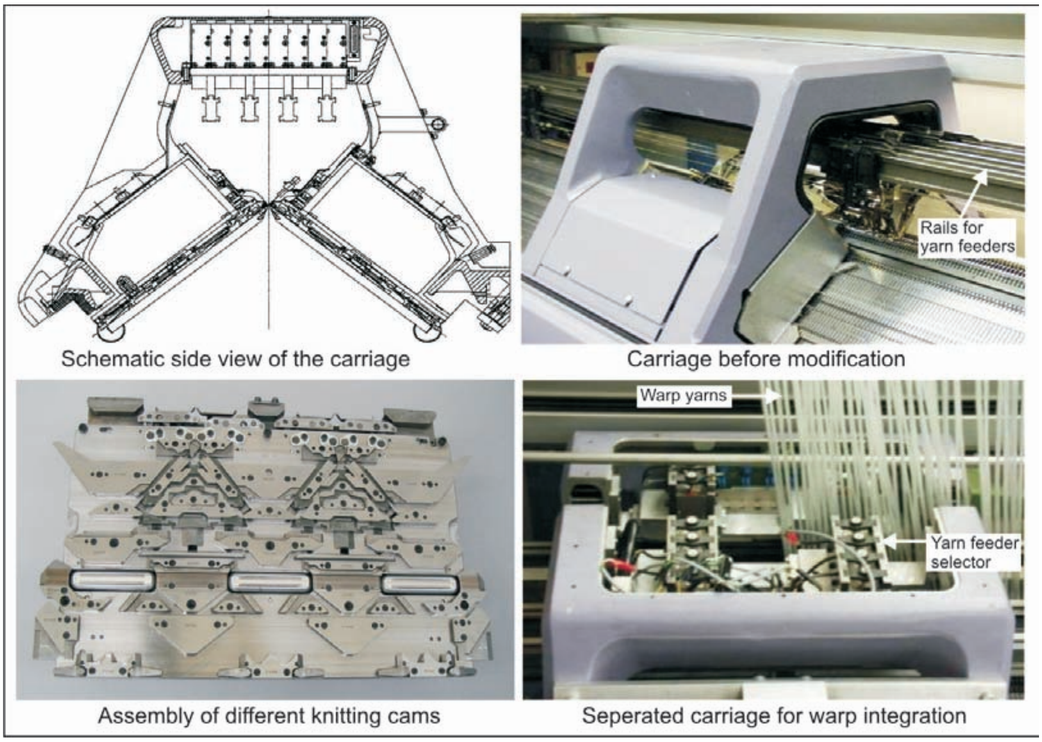


Figure 5.3: Carriage of Stoll CMS 320TC flat knitting machine

box unit has two sets of complete knitting system, whereas each knitting system is consisted of different cam systems (e.g. knit, tuck, miss, transfer) and selection sensors. These selection elements could select up to single needle in any stroke of the carriage based on CAD-pattern. Due to such diverse needle selection capabilities, complex shaped knit structures are possible to manufacture on this flat knitting machine. Again, yarn carrier selectors are electronically controlled and allow activating or deactivating the yarn feeders to traverse with carriage following CAD-pattern. In this way, various yarns feeders are used to supply the necessary yarns (base loop, weft or functional) to the knitting zone. The Figure 5.3 shows the carriage of Stoll CMS 320TC flat knitting machine.

5.1.3.3 Needle bed

The both needle beds, which are arranged in V-shaped keeping a distance 5 mm from each other at the top, are 1270 mm in width. The machine gauge is 5 needles per inch and is remained unchanged for the spacer fabric manufacturing. The needle beds also contain the needles, holding-down sinkers, knock-over sinkers and selection sinkers. However, only the rear needle bed is adjustable (racking) up to 5 needles in both directions comparing to the front needle bed position. Figure 5.4 (a) shows the needle beds of Stoll flat knitting machine.

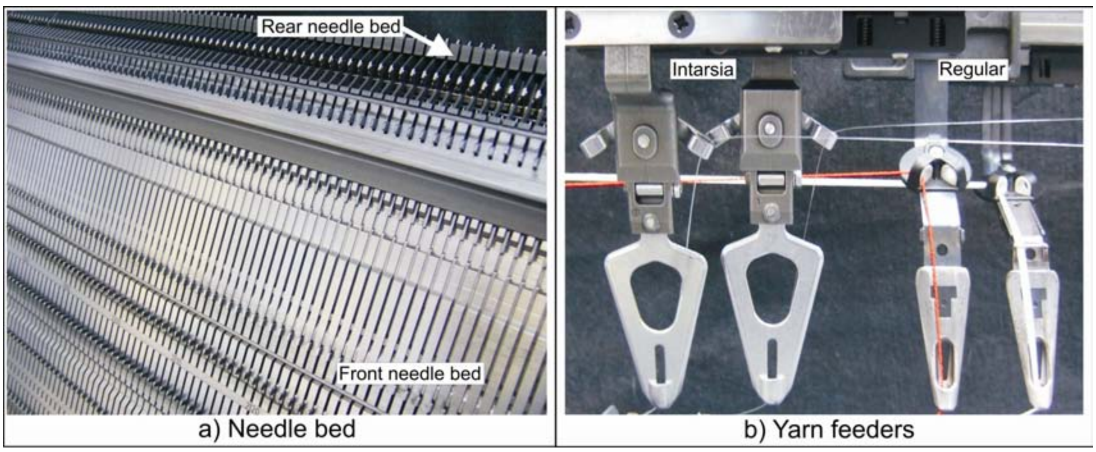


Figure 5.4: Needle bed (a) and yarn feeders (b) of Stoll CMS 320TC flat knitting machine

5.1.3.4 Yarn feeder

Different types of yarn feeders, for instance, regular, platted and intarsia yarn feeders can be used on Stoll flat knitting machine. However, only the regular and intarsia yarn feeders are used to develop 3D spacer fabrics. The regular yarn feeders are used to carry the finer loop yarns (138 tex) and coarser reinforcement yarns (up to 1230 tex). Conversely, the intarsia yarn feeder is used to integrate the functional yarns for "sensor-network" into the course directional reinforced 3D spacer fabric structure. The yarn feeders are placed usually on the rails above the needle beds (below the yarn feeder selection unit of carriage). There are maximum 8 yarn feeders could be traversed on 4 rails (2 yarn feeders on each rail). Nevertheless, due to the previous modification at carriage, 3 rails are now available on this flat knitting machine allowing maximum 6 yarn feeders to be employed. The figure 5.4 (b) shows the used yarn feeders of this experiment.

5.1.3.5 Knitting zone and knitting elements

The knitting zone is composed of the carriage, needle beds, needles, yarn feeders, holding down sinkers and the knock-over sinkers. The knitting zone of Stoll CMS 320TC flat knitting machine is shown in Figure 5.5. The needle beds could be arranged in interlock or rib gating depending on the knit patterns. The knock-over sinkers and the holding down sinkers are placed at the top between the adjacent needles. However, the latch needle along with patent sinker, pattern sinker and selector are positioned in the groove of the needle bed. These knitting elements are guided by the knitting cams and electro-magnetic selectors based on CAD-pattern. For example, patent and pattern sinkers are responsible to activate or deactivate the needle in knitting, where the different stitch formation is done by guiding the needle butt and selector.

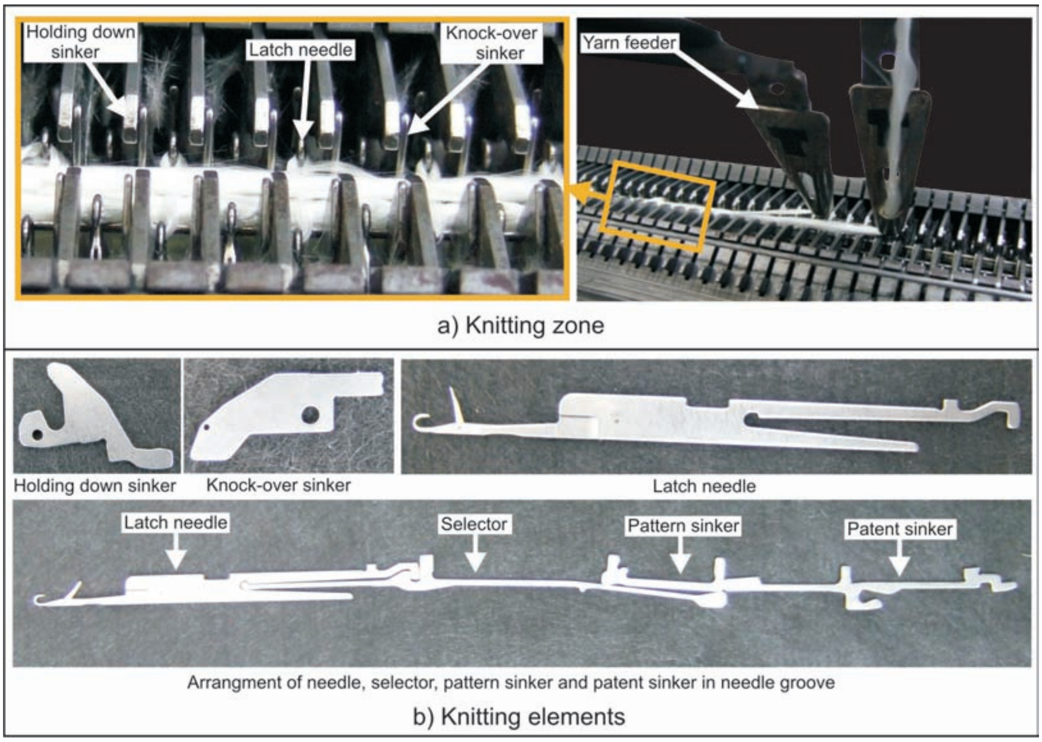


Figure 5.5: Knitting zone and knitting elements

5.1.3.6 Take-down system

The fabric take-down system is comprised with three different take-down units, which are the main take-down unit, upper take-down unit (additional take-down system) and the holding down sinkers. The main take-down unit consisting of two rubber-coated rollers pressing each other is arranged at the bottom of the machine and provides the take-down motion over the knitted fabrics. Between the two rollers, front roller is the segments of rollers connected with individual spring systems. On the other hand, the upper take-down system, which is placed under the needle beds, is consisted of two small aluminium-profile rollers. This take-down system provides additional take-down forces on the knitted fabrics. The level of take-down forces of both main and additional take-down units is programmable by CAD system. Conversely, holding down sinkers are attached at the front edges of both needle beds and guided by the special cams of carriage. The fabric held by the needles is thus trapped under these sinkers and prevented from further moving. Regardless of the operation mode of the take-down mechanism, the fabric is prevented from riding up with the ascending needles, which are able to clear their old loops and knit new loops. This is especially true when some of the loops should be held while others knit repeatedly. Another important advantages of this system is that in a case of a press-off, the fabric can be easily “pressed-on” again simply by threading the carrier and resuming the knitting operation. However, for the development of spacer fabrics with diverse geometries,

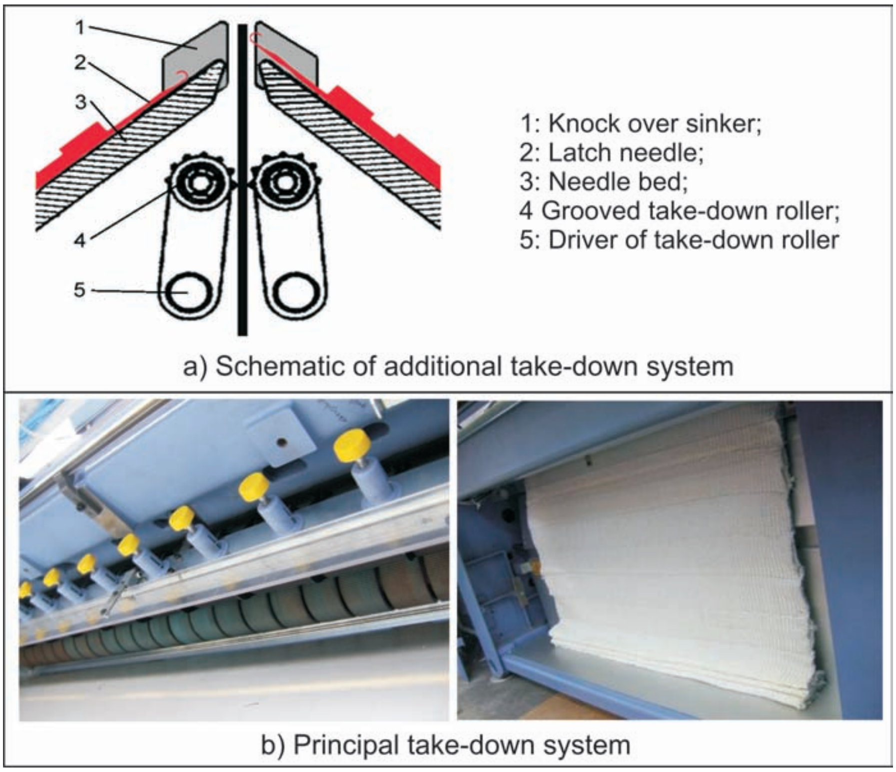


Figure 5.6: Take-down systems of Stoll CMS 320TC flat knitting machine

the holding down sinkers play a major role, especially in the construction of variable connecting fabrics. In spacer fabric knitting, the main take-down system is kept inactive while knitting the connecting fabrics. The connecting fabrics are then pressed downwards by holding down sinkers into the gap between needle beds providing adequate fabric take-down force for effortless knitting. The main and additional take-down systems are presented in Figure 5.6.

5.1.4 Flat knitting machine: Steiger Aries.3

The Aries.3 flat knitting machines also belong to the modern fully-fashioning flat knitting group and they are prominent for an assortment of 2D/3D knitting with fully-fashioned and shaped edges along with jacquard, plated and intarsia patterns with individual needle selection capability. Aries.3 flat knitting machine is different than Stoll CMS 320TC flat knitting machine in various viewpoints, for example, in carriage construction, number of knitting head existing, presence of intermediate sinkers, type of yarns feeders, type of needle and other knitting elements. However, two different Aries.3 flat knitting machines (conventional & advanced) are selected for the development of multi-layer reinforced 3D spacer fabrics. These machines differ each other only regarding the available distances between the needle beds (e.g. 5 mm & 10 mm) and number of yarn feeders in hand. Conversely, these flat knitting machines have already been modified at ITM, TU Dresden, especially in the take-down system for multi-layer knitting [26]. Nonetheless, the major technologies of these flat knitting machines are discussed briefly in the following subsections.

5.1.4.1 CAD-patterning software: Model

Aries.3 flat knitting machines are compatible with the Model CAD-patterning software. The simplicity in creation and the usage of its logic symbols make the user independent in designing of effortless knitting program. The program offers a very important base library that is being constantly updated and enlarged and that can be freely customized by the user. Moreover, the program analyses the pattern feasibility and dis-

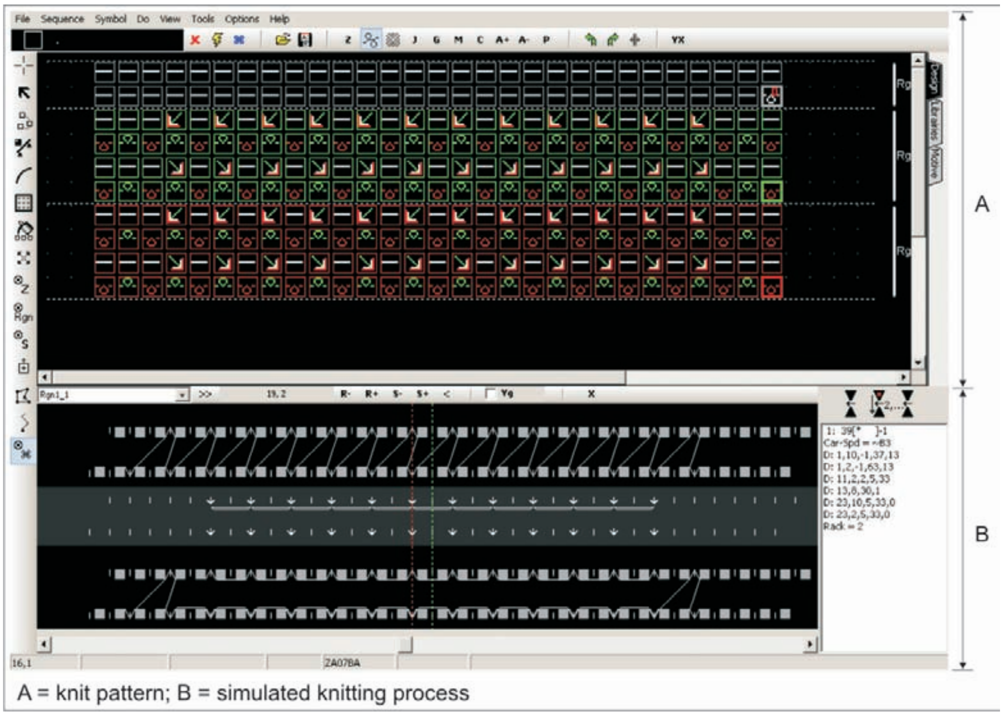


Figure 5.7: Example of 2D knit pattern (single jersey with loop transfer) and simulated knitting process by Model CAD-system

plays a simulation of the knitting process, thus really helping the user to understand the formation of stitch structures. With a few instructions, this Model version allows from a BMP format graphic design to automatically create the whole program while optimizing the production time. However, complex shaped 3D spacer fabrics with multi-layer reinforcements are designed successfully using the latest version (Version 7 & 8) of Model CAD-patterning software. The Figure 5.7 shows the example of knit pattern and knitting process by Model CAD-system.

5.1.4.2 Carriage

The innovative construction of open carriage resulted in the elimination of the bow of the cam-carriage so that the front and rear units of the carriage are able to work independently. The complete synchronization of the carriage-units is ensured by using a single motor for driving them. The

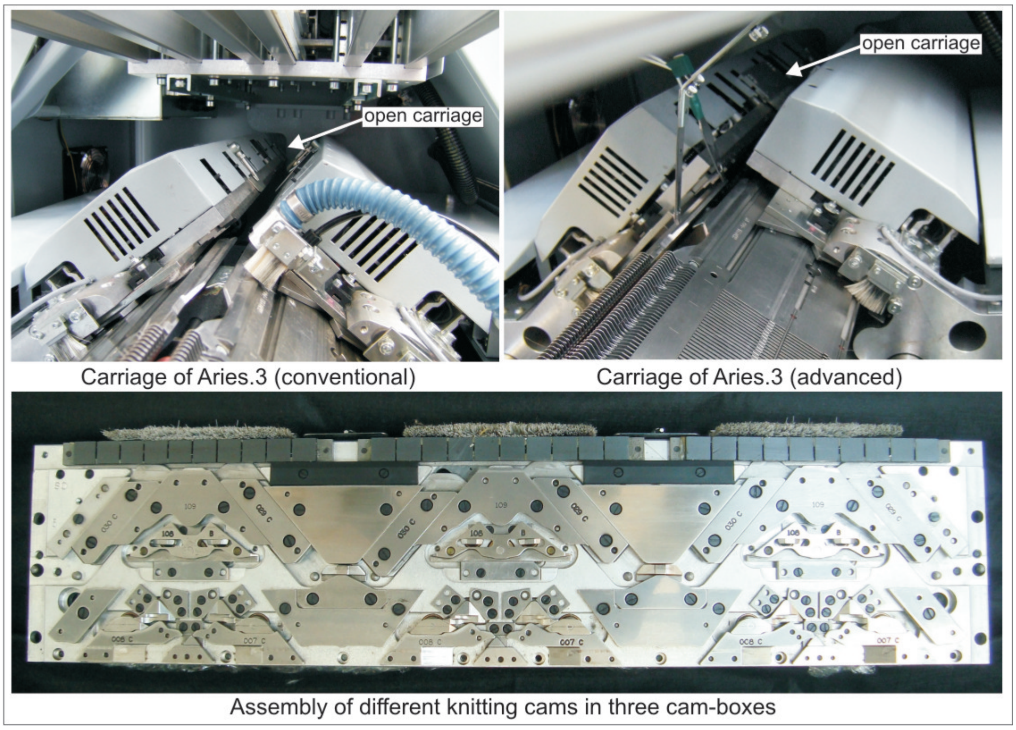


Figure 5.8: Carriages of Aries.3 flat knitting machines

open carriage design offers the yarn feeding directly from above including the reduced yarn friction. Moreover, the open carriage combined with the individual motorization of the yarn-carriers has made it possible to separate the control of yarn-carrier movements completely from that of the cam-carriage. Consequently, it is possible to integrate the reinforcement warp yarns through the open carriage for multi-layer reinforcements in the development of 3D spacer fabric. However, three com-box systems (consisting of different knitting cams) are equipped to the backside of each carriage-unit so that they could drive the needle butts and other selecting elements while the carriage is traversed over the needle beds. The Figure 5.8 shows the carriages of Aries.3 flat knitting machines.

5.1.4.3 Needle bed

The both Aries.3 machines are common in terms of needle beds arrangement (in V-shaped), machine gauge (7 needles per inch), machine width (1300 mm), arrangements of knitting elements in the needle groove, racking (only front needle bed in both sides up to 60 mm), etc. However, the distances between the needle beds of both conventional & advanced Aries.3 flat knitting machines are 5 mm and 10 mm respectively. The arrangement of needle beds of Aries.3 (advanced) flat knitting machine is shown in Figure 5.9 (a).

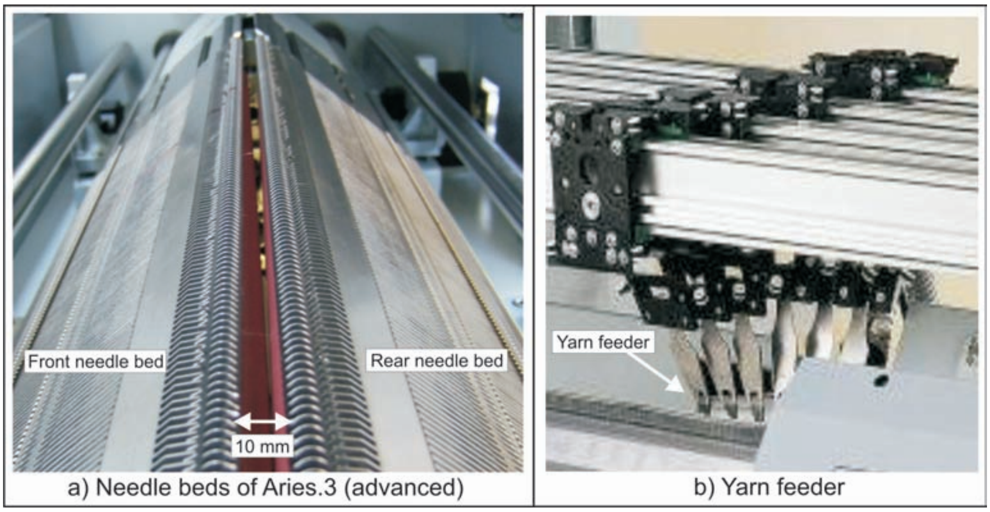


Figure 5.9: Arrangement of needle beds and yarn feeders of Aries.3 flat knitting machine

5.1.4.4 Yarn feeder

The yarn feeders are no longer driven by plungers on the upper part of the carriage bow, but by individual motors placed at the end of the yarn feeder bars. The movement and the position of the motorized yarn feeders are followed by the CAD-pattern system, which is compatible with the functions and independent from the direction of the cam-carriage movements. Such motorization of the yarn feeder offers more scopes in creativity and even in reproducibility of most complex designs combined with maximum productivity. The Aries.3 machine can be equipped with up to 32 yarn feeders. However, the conventional Aries.3 flat knitting machine has been designed with 24 yarn feeders allowing more spaces at the knitting zones, especially to accommodate coarser yarns in multiple layers for the development of multi-layered knit preforms. The yarn feeders of Aries.3 are shown in Figure 5.9 (b).

5.1.4.5 Knitting zone and knitting elements

Knitting zone and knitting elements of Aries.3 flat knitting machine are shown in Figure 5.10. The latch needles and selectors are placed in the

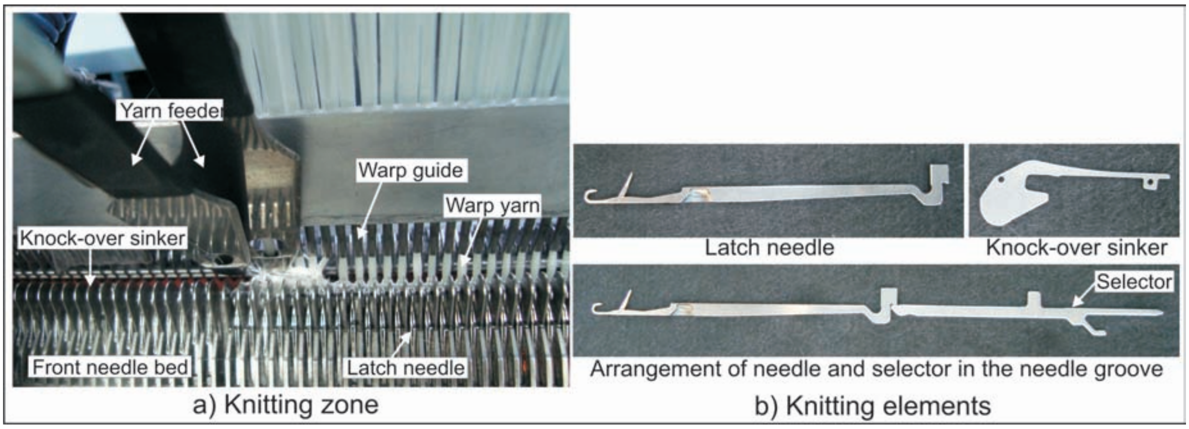


Figure 5.10: Knitting zone and knitting elements of Aries.3 flat knitting machine

needle grooves of needle beds. The knock-over sinkers are fixed at the top of the needle beds in adjacent positions of the needles. The driving of knitting elements with activation of respective cams in the carriage, the selection, usage and positioning of selected yarn feeders in every stroke of the carriage are pre-designed and simulated by the CAD-pattern system.

5.1.4.6 Take-down system

The Aries.3 flat knitting machines (both conventional & advanced) are equipped with unique upper take-down devices. The system operates at a distance of 20 mm below the loop-formation area. It consists of two rubber sleeves, which operate at slow speed in an opposite direction to each other. This ensures a rotating take-down grip on the fabric which guarantees a regular friction take-down. The system offers many advantages, for example, the elimination of pressure jacks, take-down combs, "Banana" formation of stitches. Nevertheless, for the effortless taking-

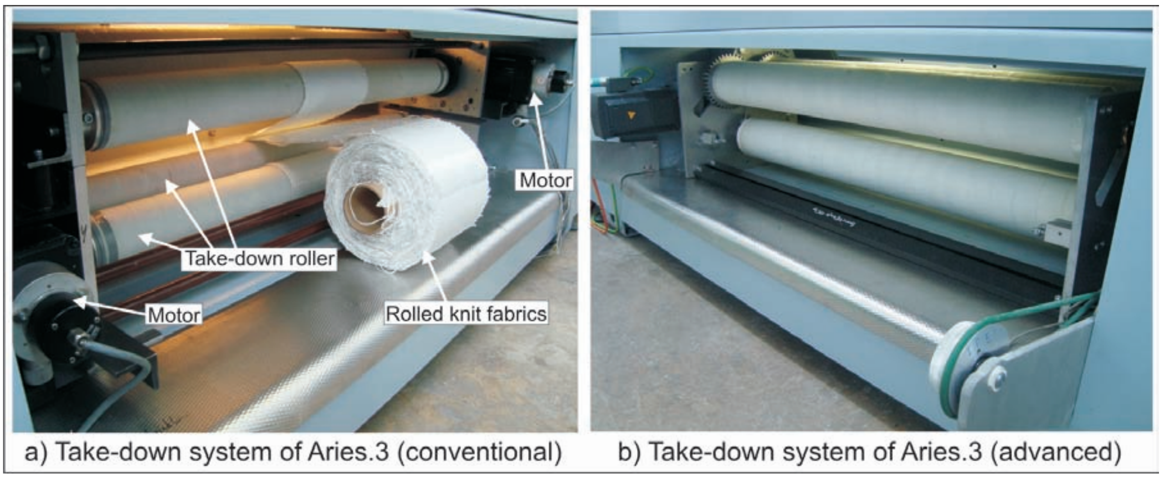


Figure 5.11: Additional take-down systems of Aries.3 flat knitting machines [26]

down of multi-layered textile preforms from relatively coarser yarns an additional take-down system has already been integrated in both Aries.3 flat knitting machines [26]. This take-down system, which is equipped at the bottom of the machine, is consisted of four take-down rollers (rubber-coated) driven by servo-motors. The Figure 5.11 presents the additional take-down systems of Aries.3 flat knitting machines.

5.2 Materials

The innovative flat knitting technology for 3D spacer fabrics offers the full flexibility of the usage of wide-spectrum of materials, for instance, from conventional fibers to high performance materials (GF, AF, CF, Metallic, etc.). With the aim of manufacturing the composites through thermoplastic consolidation, hybrid yarns consisting of E-glass (volume: 52%) and polypropylene filaments (volume: 48%) are used for the development of 3D spacer fabrics. These hybrid yarns are developed as well as manufactured at ITM, TU Dresden (Germany) in the framework of the research program SFB639 "Textile-reinforced composite components for function-integrating multi-material design in complex lightweight applications" of the German Research Foundation [26]. The modified polypropylene filaments "Prolen H" by the Chemosvit Fibrochem a.s. Company of Slovakia [112] and the special coated glass filaments by the P-D Glasseiden GmbH Oschatz Company of Germany [113] are used for the manufacturing of hybrid yarns. The yarn fineness is selected 138 tex as the knitting yarn for base fabric (base loop yarn) and 410 tex as the reinforcement yarn. However, reinforcement yarns with different finenesses are used in various perspectives, for example, as 410 tex, 820 tex and 1230 tex, which are simply multiplying the 410 tex yarn with required numbers. Moreover, a list of functional materials, for example, carbon filament, copper wire are integrated into the spacer fabric structures in oder to create "sensor-networks".

5.3 Development and manufacturing of 3D spacer fabrics

5.3.1 Structural variation of 3D spacer fabrics

The demand of spacer shaped multi-layer reinforced textile preforms with intricate geometries is immense, especially for lightweight composite applications, for example, for the multifaceted automobile body parts, namely, floors; decks; doors; bonnets; containers for motors, gear-boxes, batteries, oil pan module; crash elements; ballistic shields; body armour. Consequently, different geometrical diversification of 3D spacer fabrics is inevitable in order to develop compatible textile preforms for such complex shaped composite-components. The efficient designing of 3D spacer fabrics along with multi-directional reinforcements are indispensable in order to manufacture spacer shaped 3D composites suitable for high mechanical performances. However, innovative 3D spacer fabrics with diverse geome-

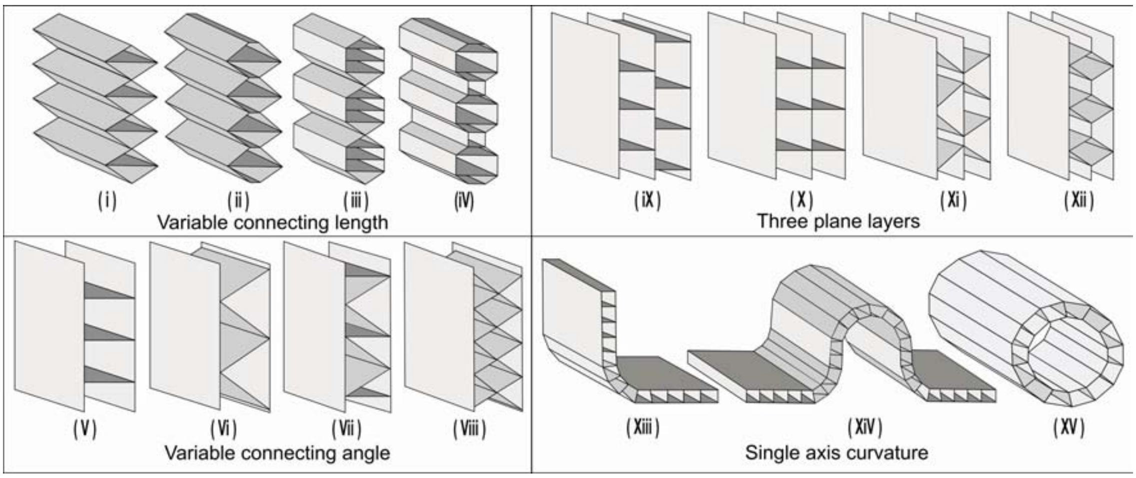
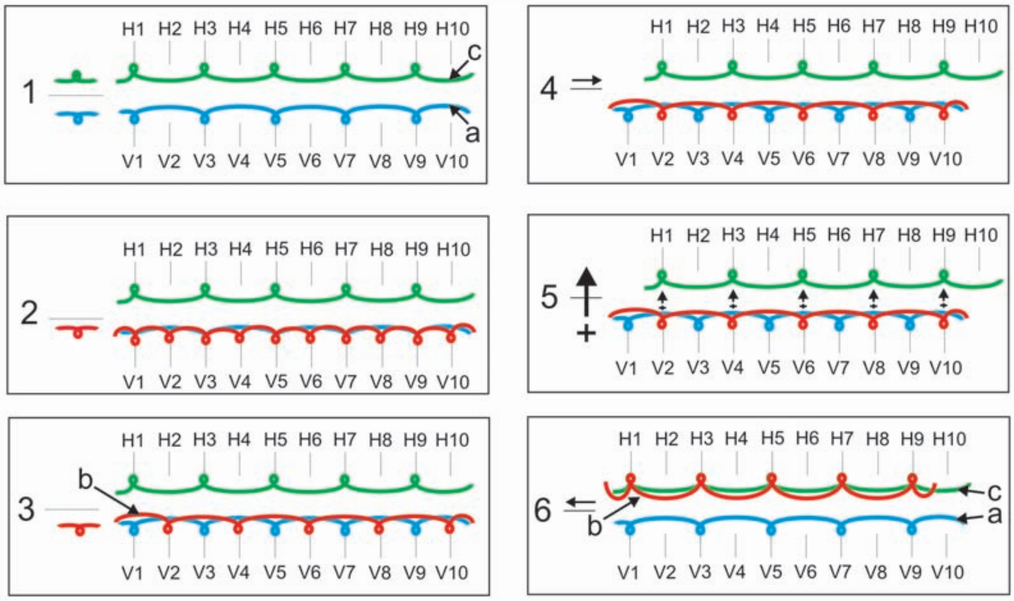


Figure 5.12: Schematic of 3D spacer fabrics (example of structural variations)

tries could be manufactured on modern flat knitting machines by further developing of knitting technologies as well as of manufacturing processes. These spacer fabrics could be categorized on the basis of number of surface layers, the curvature of the plane layers and the length and angle of connecting fabrics between the planes. The schematic structures of the designed 3D spacer fabrics are presented in Figure 5.12. These innovative 3D spacer fabrics are expected to show very improved mechanical properties. For example, the spacer fabric type (V) in Figure 5.12 is expected to be suitable against compression, tension and flexural stresses as well as for energy absorption in impact, whereas the spacer fabric type (Vi) would be very effective against shear and flexural stresses in addition to energy absorption in impact. Since the spacer fabric type (Vii) is the combination of spacer fabrics (V) and (Vi), reasonably, such spacer fabric is expected to be very promising in carrying of compression, tension, shear and flexural forces along with for impact properties.

5.3.2 Development and manufacturing of 3D spacer fabrics without any reinforcements

Considering the high complexity of the development of 3D spacer fabrics consisting of multi-layer reinforced surface and connecting layers, 3D spacer fabrics are considered to develop at first without any reinforcement (by only knit loops using finer yarns) by means of the innovative knitting technique. Once the innovative spacer fabrics are realized successfully, the necessary reinforcements (in course & wales directions) of the surface and connecting layers could be achieved by the further developments of flat knitting technology (by innovative integration concepts). However, spacer fabrics are developed by creating individual plane and connecting layers made of single jersey structures. The fineness (gauge) of needles for fabric layers is determined considering the number of individual fabric layers (plane & connecting) to be knitted for the designed spacer fabric. To knit individual fabric layers of spacer fabrics, needles of both needle beds are first grouped accordingly. For example, for knitting of spacer fabric type (V) of Figure 5.12, which is consisted of two plane layers connected vertically with individual fabric layers, the needles of each needle bed are divided into two sets: odd and even needles (Figure 5.13). Then, two independent plane layers (a, c) are knitted separately to a predetermined length (equal to both needle beds) on the odd needles of both needle beds respectively (knitting sequence 1 of Figure 5.13). Then, keeping both plane



1: Knitting of front & rear plane layers individually, 2: Knitting course on front needle bed, 3: Knitting of connecting layer; 4-6: Shifting of connecting layer from front to rear needle bed, V: Needles of front needle bed, H: Needles of rear needle bed, ⊸: Knit loop, ↑: Loop transfer from front needle bed to rear needle bed, → & ← Racking direction of rear needle bed, a: Front plane layer, b: Connecting layer, c: Back plane layer,

Figure 5.13: Binding technique (example) of 3D spacer fabric (type-V) without any reinforcement

layers idle, a connecting course is knitted on all needles of front needle bed (knitting sequence 2 of Figure 5.13). On the very next, knitting is followed consecutively only on the other alternate needles (even) of front needle bed to form the connecting length (b) with a predetermined length (knitting sequence 3 of Figure 5.13). At the end, connecting layer (b) is shifted to the odd needles of rear needle bed using loop transfer technique to have a perpendicular connection between the planes (knitting sequence 4-6 of Figure 5.13). The aforementioned knitting sequences (1 to 6 of Figure 5.13) together are a repeat of manufacturing 3D spacer fabric type (V). On the other hand, the alignment of needles of each needle bed are in three different sets for the spacer fabric type (Viii) of Figure 5.12, which is consisted of two plane layers (a, c) and two connecting layers (b, d). Two needle sets of each needle bed are used to construct the relevant plane and connecting layers respectively. For instance, plane layer a and connecting layer b are on front needle bed, whereas plane layer c and connecting layer d are on rear needle bed. The remaining needle set of each needle bed is used to accommodate the other connecting layer of the opposite needle bed for the effortless knitting of the opposite plane layer. However, the spacer fabrics from type (i) to type (Xii) shown in Figure

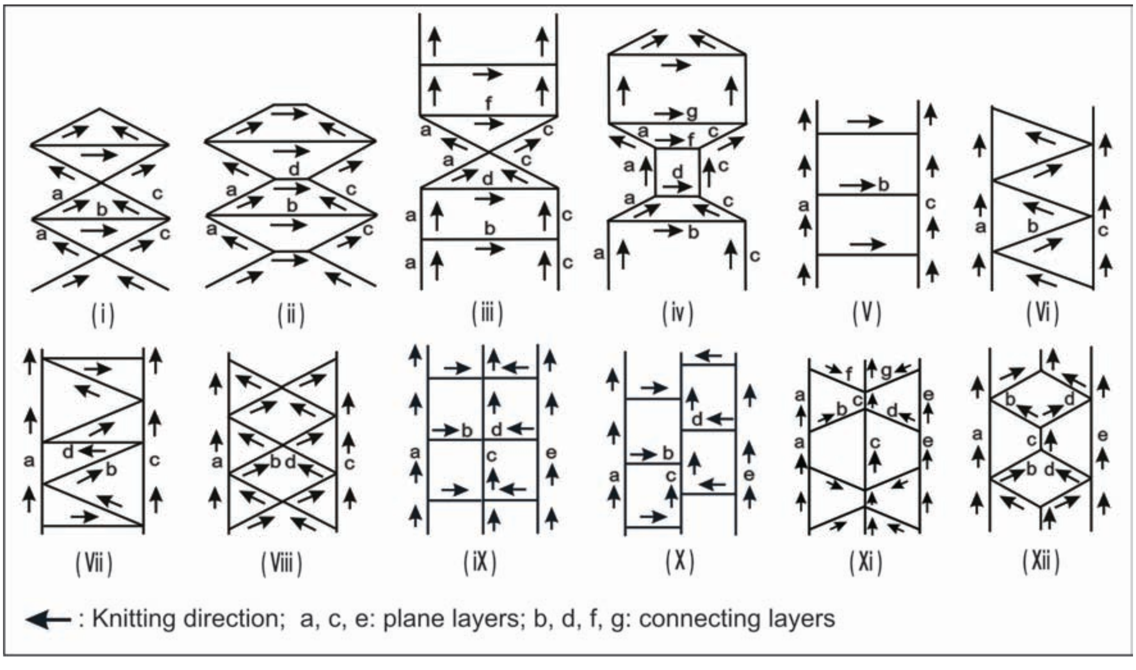


Figure 5.14: Schematic knitting phases in manufacturing of 3D spacer fabrics

5.12 are knitted on the Stoll CMS 320TC flat knitting machine without any integration of reinforcement yarns into fabric structures. Finer loop yarn is used to construct these 3D spacer fabrics following single jersey knit patterns. The different knitting phases (directions) in manufacturing of such spacer fabrics are shown in Figure 5.14. For the construction of spacer fabric type (i), two plane layers (a, c) are knitted separately on the selected needles of both front and rear needle beds. The connecting layer (b) is then knitted on the selected needles of front needle bed keeping the planes idle and finally shifted to rear needle bed to form a perpendicular connection. Later on, both planes are knitted to a predetermined length, joined together following an interlock or rib course and, finally, knitted again separately to construct both independent plane layers. The construction of spacer fabric type (ii) is quite similar to the spacer fabric type (i). In this case, both plane layers are joined vertically with connecting layers (b, d) of two variable lengths arranged alternatively. The spacer fabric type (iii) is the combination of spacer fabric types (i) and (V), in which both planes (a, c) are connected vertically with three individual and alike fabric layers (f, b, d) in three different phases keeping the same distance between two neighbouring connections. On the very next, both planes (a, c) are knitted to a predetermined length, joined together following an interlock or rib course and knitted again separately to construct the independent planes. On the other hand, the spacer fabric type (iV) is knitted following the construction of two independent planes (a, c) connected vertically with two separate fabric layers (with a predetermined length between two neighbouring connections), in which every two consecutive connecting layers (b, g and d, f) are knitted in dissimilar lengths by turns. For spacer fabric type (V), two individual surface layers (a, c) are knitted on front and rear needle beds, and then joined with a connecting layer (b) vertically. Among the three knitted layers created on both needle beds for spacer fabric type (V), middle connecting layer (b) is joined with both surface layers (a, c) by turns keeping a constant length to get spacer fabric type (Vi). Type (Vii) is the combination of spacer fabric types (V) and (Vi). For spacer fabric type (Viii), four individual layers (a, b, c, d) are knitted on front and rear needle beds (for instance, layers a and b on front needle bed and layers c and d on rear needle bed), and finally the middle connecting layers (b, d) are joined together and then with the plane layers (a, c) respectively by turns keeping a constant length. In order to construct spacer fabrics (iX) and (X), three surface layers (a, c, e) are knitted first on both needle beds. The first and middle surface layers (a, c), and the third and middle surface layers (e, c) are joined vertically with two connecting layers (b, d) respectively to get spacer fabric type (iX). For spacer fabric type (X), the three surface layers (a, c, e) are knitted individually for a definite length after joining vertically only the first and middle surface layers (a, c) with a connecting layer (b). The third and middle surface layers (e, c) are then joined vertically with a new connecting layer (d). The construction of spacer fabric type (Xi) is very much complex, where three surface layers (a, c, e) are joined with four individual connecting layers (b, d, f, g) in different phases of knitting cycle. For spacer fabric type (Xii), four individual layers (a, b, d, e) are knitted on front and rear needle beds (for instance, layers a and b on front needle bed and layers d and e on rear needle bed). The middle connecting layers (b, d) are then joined together to form the middle plane layer (c) and, on the very next, all three plane layers (a, c, e) are knitted to a predetermined length. Finally, the middle plane layer (c) is then divided into middle connecting layers (b, d), knitted to a fixed length and joined with the surface layers (a, e) respectively. The developed innovative 3D spacer fabrics without any reinforcement into fabric structures are presented in Figure 5.15.

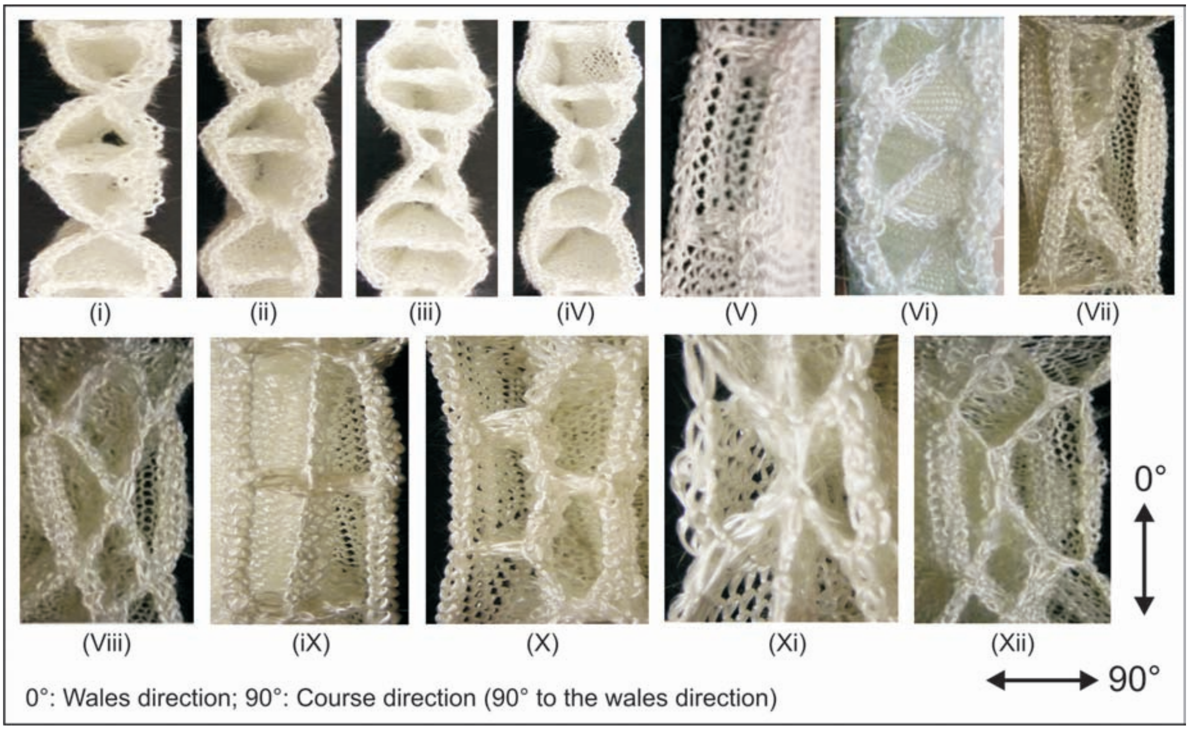


Figure 5.15: Flat knitted innovative 3D spacer fabrics using 138 tex GF-PP hybrid yarns (without any reinforcement)

3D spacer fabrics with diverse geometries are developed successfully using the innovative flat knitting technologies and manufacturing techniques. Such innovations permit the fully realization of complex shaped 3D spacer fabric structures from only single stage-manufacturing process, whereas the multifaceted designing of fabric structures would offer various structural benefits (form follows force), for instance, rigidity, energy absorption, tensile strength (in tension and compression). Conversely, the above mentioned 3D spacer fabric structures, which are expected to be compatible for proper structural superiorities based on the end uses of the composites, could be selected, reinforced further and utilized as textile preforms in composite-moulding process.

5.3.3 Concepts for the integration of reinforcement yarns into knit structures

In order to apply in high-load conditions, 3D spacer fabrics must have to be reinforced enough by integrating the reinforcement yarns into the fabric structures. With the intention of reinforcing the spacer fabric structures, various concepts for the integration of reinforcement yarns into knit structures are developed. One of the aims of such innovation is to check the possibility of integration of reinforcement yarns by flat knitting. However, reinforcement yarns are integrated successfully into 2D knit structures following five different integration techniques, for example, as knit loop, tuck stitch, weft yarn (weft inlay), warp yarn (warp inlay) and as weft & warp yarns (as biaxial inlays). These integration methods have been documented in Figure 5.16. Flat knitting machine CMS 320TC is used to integrate the reinforcement yarn as knit loop, tuck stitch and weft yarn, whereas the flat knitting machine Aries.3 (conventional) is used to integrate as warp yarn and as multiple layers (biaxial inlays). In case of knit loops, the reinforcement yarns are used to construct the knit loops directly following single jersey knit pattern. But, the reinforcement yarns are integrated as tuck stitches and as weft yarns into the single jersey knit fabrics using finer yarns. In the method of tuck stitch shaped integration, every alternate needle (for example, odd needles of front needle bed) is used first to construct knit loops using finer yarn. On the very next, the remaining needles (even needles of front needle bed) are driven to construct tuck stitches using the coarser reinforcement yarn. However, a repeat of such tuck stitch shaped integration is completed when the construction of knit loops and tuck stitches are followed by the replacement of their respective needles (knit loops and tuck stitches on even and odd needles respectively). In case of the integration of reinforcement yarns as

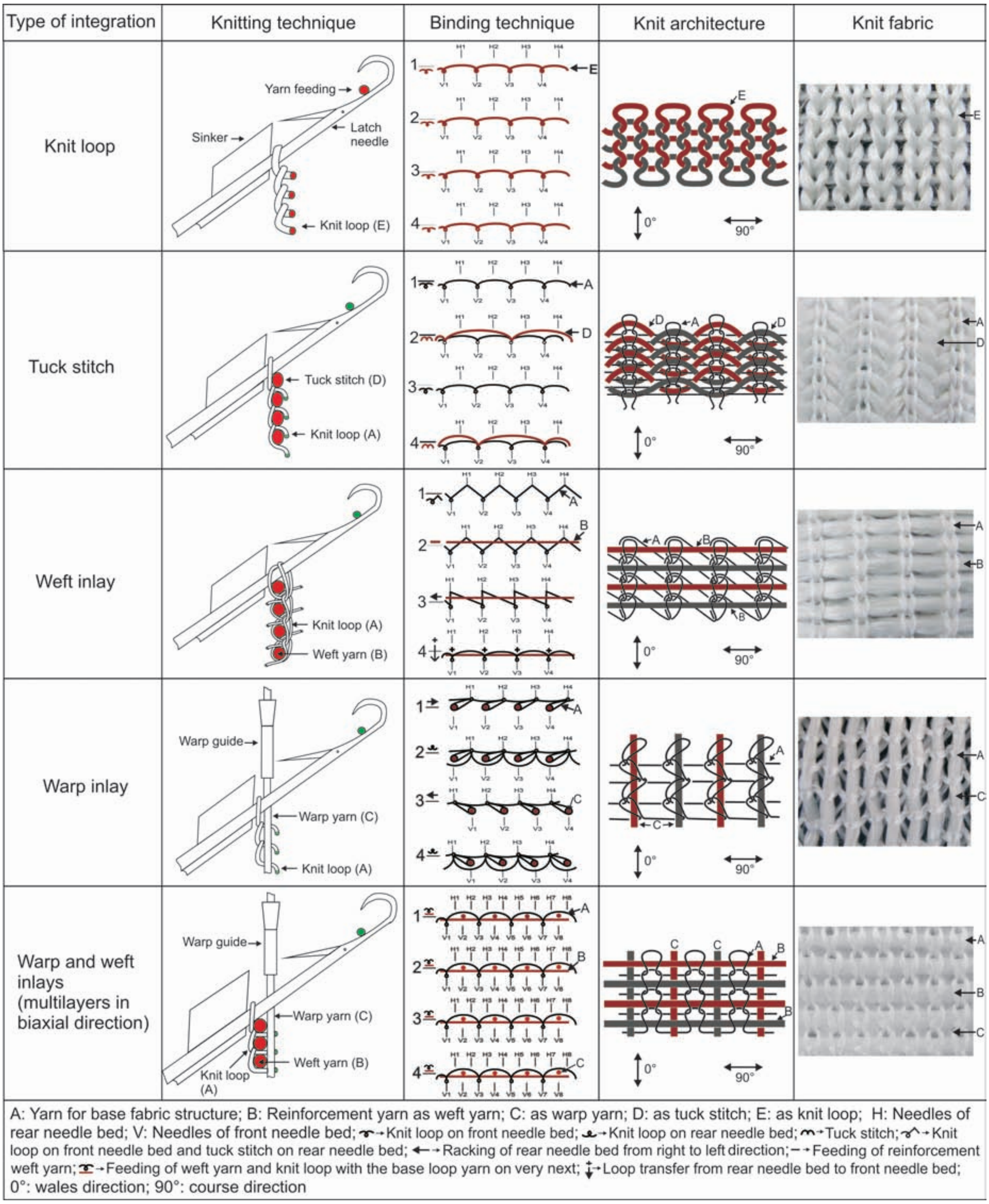


Figure 5.16: Different integration methods of reinforcement yarns by flat knitting

weft yarns, all needles of front and rear needle beds are used to construct knit loops and tuck stitches respectively using the same finer yarn. Later on, the reinforcement yarn is supplied by the yarn feeder, placed between needle beds and, finally, the tuck stitches are transferred to the needles of front needle bed so that the already placed reinforcement yarn becomes trapped as floating yarn (as non-crimp weft yarn) into knit structure. On the other hand, the warp yarns, which are delivered from above through the open carriage of Aries.3 flat knitting machine, are integrated as warp yarns in a single jersey knit-pattern using also finer loop yarn. In order to integrate the reinforcement yarns only as warp yarns, the finer base fabric yarn is delivered from the back side of the warp yarns (if it is counted from the respective needle bed), whereas the knitting is carried out only on the needles of any single needle bed. However, the warp yarns are trapped into knit structure (by the finer loop yarns) when the racking of the needle bed is followed about single needle position in both left and right directions alternatively. Conversely, the multi-layer reinforced biaxial knit fabric is produced on Aries.3 flat knitting machine using the coarser weft and warp yarns along with finer base fabric yarn. Weft and finer yarns are supplied by the yarn feeders from the front and rear sides of warp yarns respectively, if they are counted from the respective needle bed. In knitting, weft yarn is placed first between the needle bed and the warp yarns. On the very next, needles are raised up keeping the already placed weft yarns down and received the finer yarn from the back side of the warp yarns. This finer yarn is used to construct the single jersey knit structure. However, the weft yarns along with warp yarns are connected as multiple layers (as biaxial inlays) into single jersey knit structure, when the above mentioned knitting stages are cycled.

Knit structures with different arrangement of reinforcement yarns based on the above discussed innovative integration concepts are expected to show dissimilar mechanical performances both in the formation of fabrics and composites. For example, the looped shaped arrangements (as knit loops, tuck stitches) of reinforcement yarns would be suitable for high energy absorption in impact, whereas the non-crimp alignments (weft and warp inlays) would be suitable for carrying the applied forces. Such divergence of mechanical behaviours could be the results of the different orientations of fibers as well as the variable breakages of reinforcing component (GF) caused by the unlike integration of reinforcement yarns. Nevertheless, the integration of reinforcement yarns as weft and warp inlays, which are actually the non-crimp inlays into fabric structure, is considered to be the best solution for high mechanical performances in both wales and course directions.

5.3.4 Development and manufacturing of 3D spacer fabrics with course directional reinforcements

In order to develop biaxial reinforced (multi-layered) 3D spacer fabrics, the integration of reinforcement yarns into course direction is considered first. For achieving the reinforcing effect in course direction, the reinforcement yarns could be integrated into spacer fabric structure as knit loops, tuck stitches or as weft inlays (weft yarns). However, the integration of reinforcement yarns as weft inlays is expected to be the most effective arrangement of fibers due to their non-crimp alignments in course direction. Nevertheless, the spacer fabric types (V), (Vi), (Viii), (iX), (X) and (Xii) of Figure 5.12 are knitted successfully including the reinforcement yarns (410 tex) as weft inlays into all plane and connecting layers on the flat knitting machine Stoll CMS 320TC. These 3D spacer fabrics are shown in Figure 5.17. The remaining spacer fabrics of Figure 5.15 could also be knitted including weft inlays by applying additional yarn feeders on the flat knitting machine. The knitting phases (knitting directions) of manufacturing of these 3D spacer fabrics are also as same as they are in manufacturing without any reinforcement yarns (presented in Figure

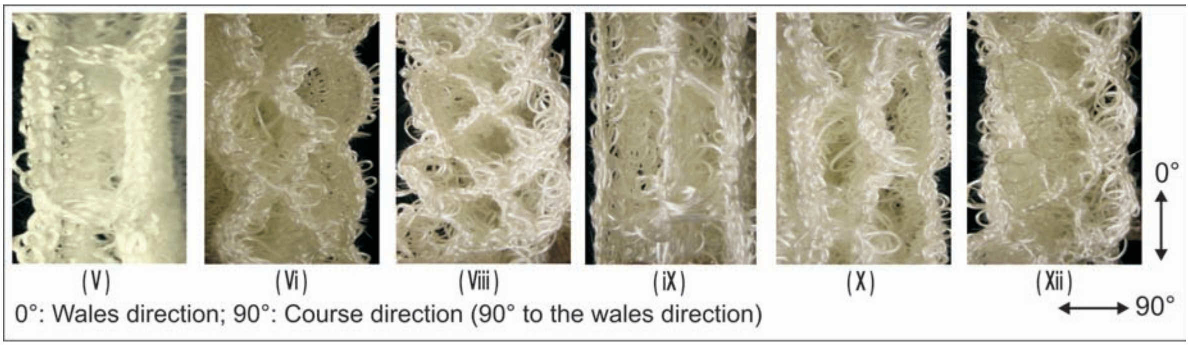


Figure 5.17: Example of 3D spacer fabrics with reinforcement yarns (410 tex) integrated as weft inlays

5.14). But, the grouping of needles of each needle bed is done taking into account not only the number of fabric layers to be knitted at a time, but also the integration technique of weft inlays (through loop transfer) into all plane and connecting layers. For instance, the binding technique of manufacturing of 3D spacer fabric (type-V) with reinforcement yarns integrated as weft inlays (through loop transfer technique) into all plane and connecting layers is documented in Figure 5.18. In knitting of this spacer fabric, the needles of each needle bed are divided into two sets: odd and even needles. Then, two independent plane layers (a, c) are knitted separately to a predetermined length (equal to both needle beds) on the odd needles of both needle beds respectively (knitting sequences 1 to 9 of Figure 5.18). The reinforcement yarns are integrated into each plane layer as weft yarns following the loop transfer technique. Then, keeping both plane layers idle, a connecting course is knitted on all needles of front needle bed (knitting sequences 10 of Figure 5.18), and on the very next, the knitting of connecting layer (b) including the reinforcement yarns integrated as weft yarns by loop transferring is followed on the even needles of front needle bed (knitting sequences 11 to 15 of Figure 5.18). Finally, the connecting layer (b) is shifted to the odd needles of rear needle bed using loop transfer technique to have a perpendicular connection between the planes

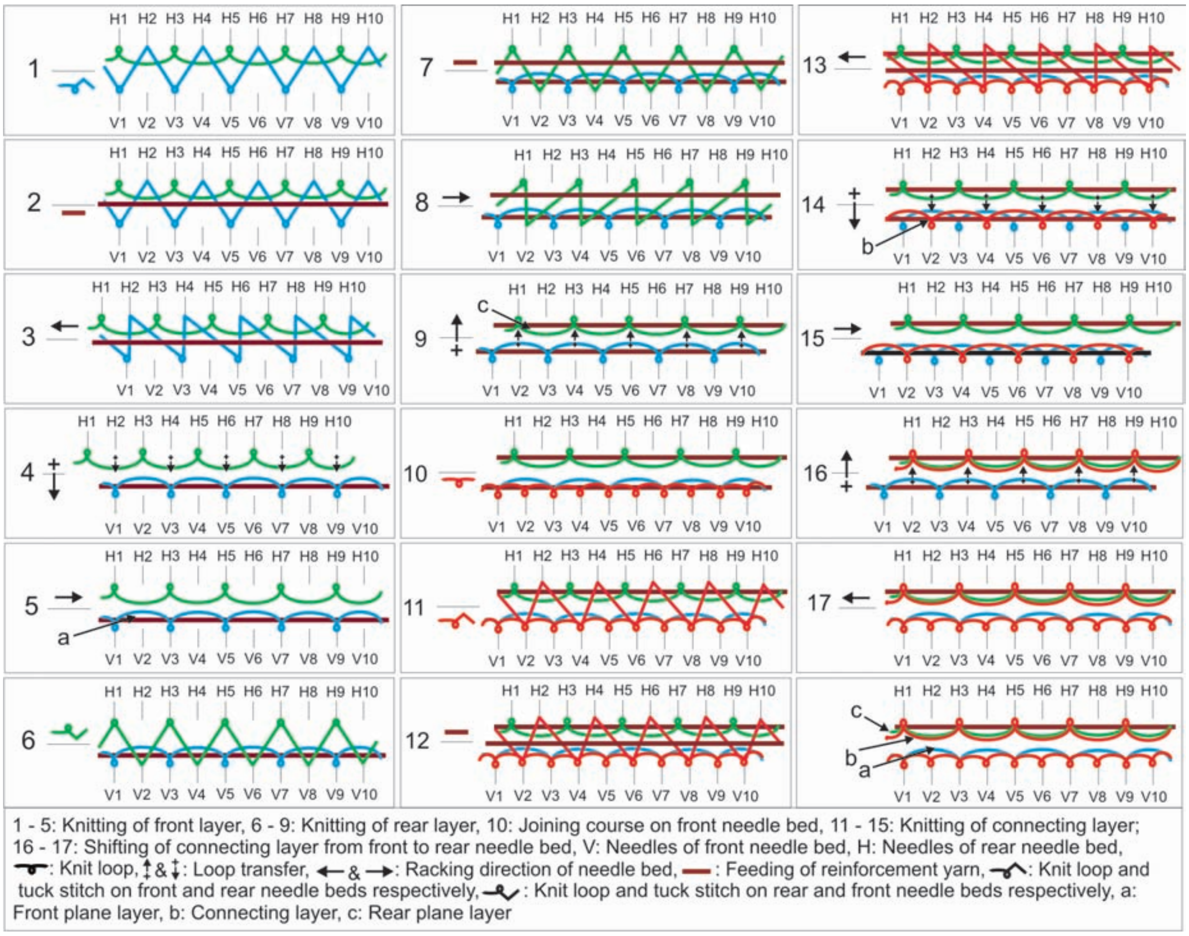


Figure 5.18: Example of binding technique of 3D spacer fabric (type-V) with integrated reinforcement weft yarns into plane and connecting layers

(knitting sequences 16 to 17 of Figure 5.18). The aforementioned knitting sequences (1 to 17 of Figure 5.18) together are a repeat of manufacturing 3D spacer fabric type (V), which is comprised with weft reinforced plane layers connected vertically with weft reinforced connecting layers. Again, this spacer fabric (type-V) is manufactured separately with integrated reinforcement weft yarn using relatively coarser yarns (1230 tex). Moreover, such coarser yarns are also integrated as knit loops and tuck stitches seperately within this spacer fabric structure. These 3D spacer fabrics are presented in Figure 5.19.

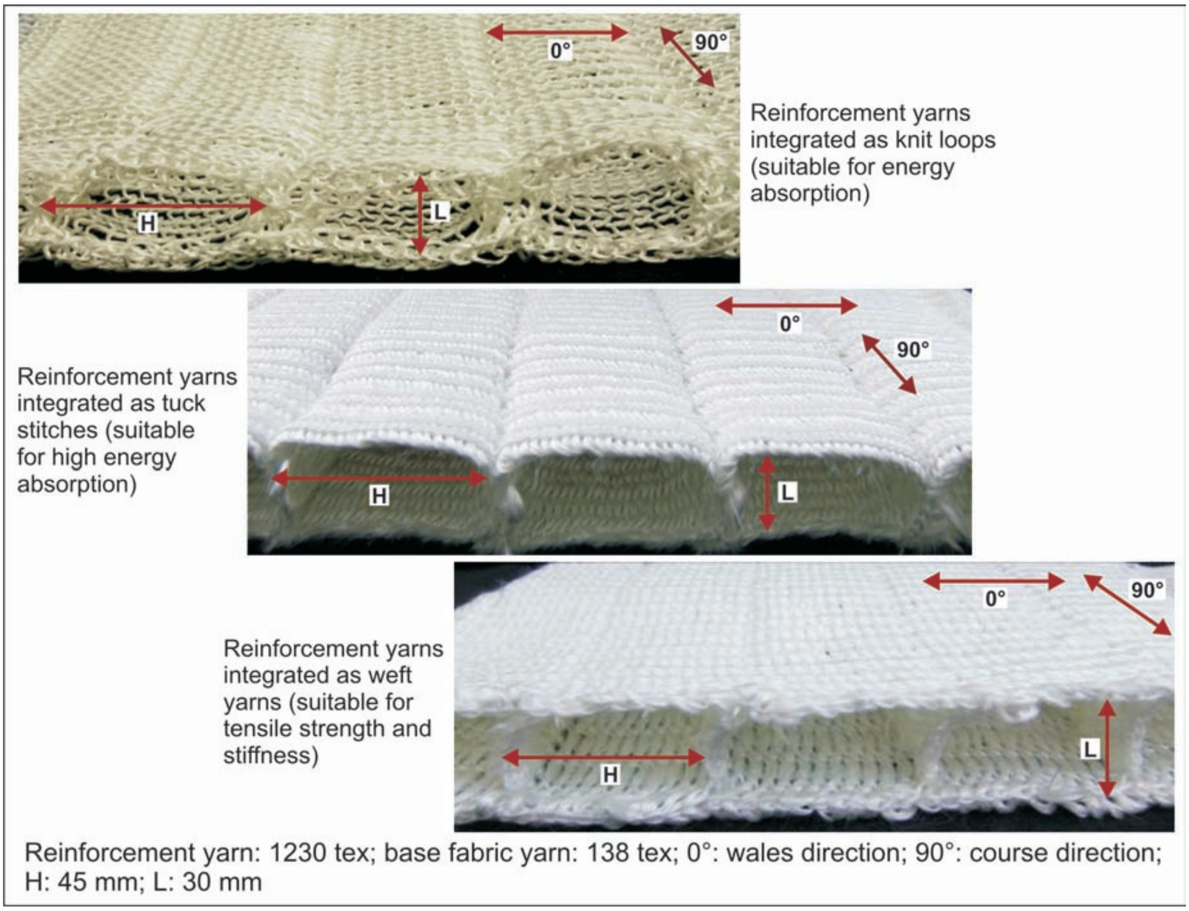


Figure 5.19: Example of flat knitted 3D spacer fabrics (type-V) with different course directional reinforcements (as knit loops, tuck stitches & weft yarns)

5.3.5 Development and manufacturing of various 3D tubular structures

Tubular structures are the 3D structures, which are comprised with two surface layers connected together at the edges by continuous fabric strands or yarns. The application potential of these tubular fabric structures is immense, especially in lightweight structures, textile reinforced concretes, industrial textiles, protective textiles, etc. Conversely, in order to use as high performance textile preforms, the development of such 3D tubular structures using favourable materials, for example, using high performance yarns, is foreseen. Conventional tubular structures are produced by weaving, braiding and knitting techniques. Weaving and braiding technologies are not considered to be feasible for high mechanical performances because of the so-called fiber-interlacements in processing and the very high investment costs. On the other hand, knitting is renowned only for the mesh structured tubes mostly for the conventional usage.

Within the frame work of the development of multi-layered 3D spacer fabrics, seven different 3D tubular structures are manufactured successfully using the novel flat knitting technologies. These new 3D tubes are manufactured individually with the integration of reinforcement yarns into knit structures as knit loops (T-K), tuck stitches (T-T), weft yarns (T-W), warp yarns (T-WA), warp yarns & tuck stitches (T-WAT), warp yarns & weft yarns as well as tuck stitches (T-WWAT), and as warp & weft yarns (T-WWA). The schematic construction techniques (innovative flat knitting), 2D knit architectures and 2D knitted structures and the already knitted 3D tubes are shown in Figures 5.20 and 5.21. The tubular structures T-K, T-T and T-W are manufactured on the Stoll CMS 320TC flat knitting machine, whereas the tubular structures T-WA, T-WAT, T-WWAT and T-WWA are produced on the Aries.3 (conventional) flat knitting machine. The integration of reinforcement yarns is followed combining the integration techniques already described in section 5.3.3. The tube T-K is knitted creating two single jersey structures on both front and rear needle beds by turns using the same reinforcement yarn. On the other hand, two yarn feeders are used (for finer and reinforcement yarns) to construct the tubes T-T and T-W. The finer yarn is first used to construct two single jersey structures on both needle beds separately by turns. The reinforcement yarn is then integrated as tuck stitches in both single jersey structures gradually to form the tube T-T, whereas the reinforcement yarn is integrated as weft yarns through loop transfer technique to form the tubular structure T-W. The usage of the same yarn feeders

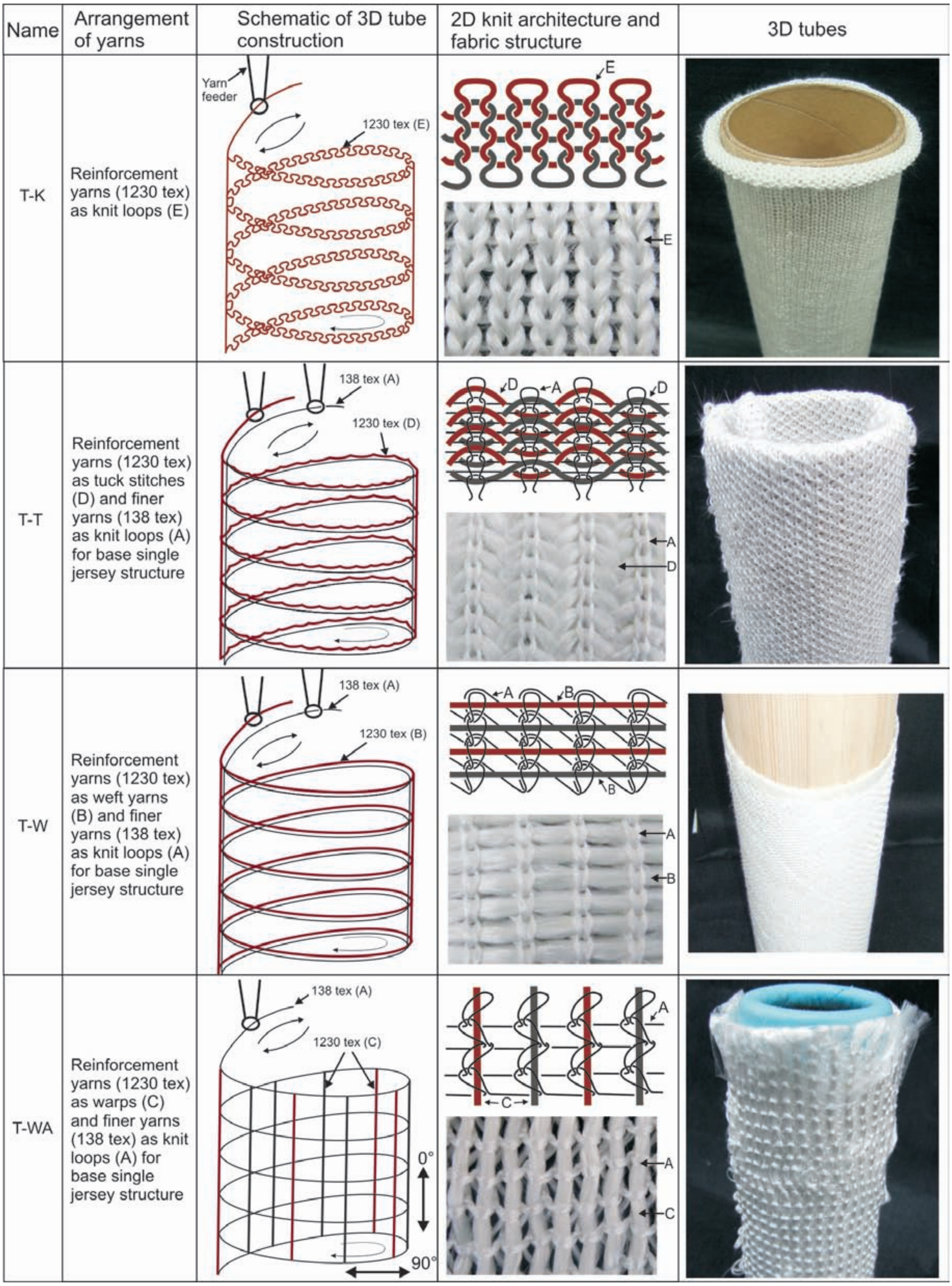


Figure 5.20: 3D tubes with integrated reinforcement yarns as knit loops (T-K), tuck stitches (T-T), weft yarns (T-W) and warp yarns (T-WA)

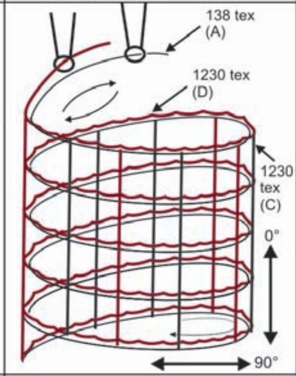
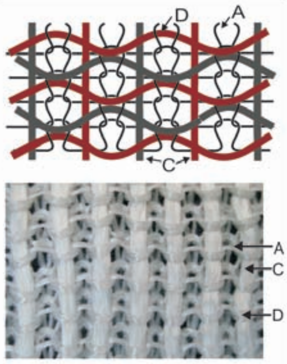
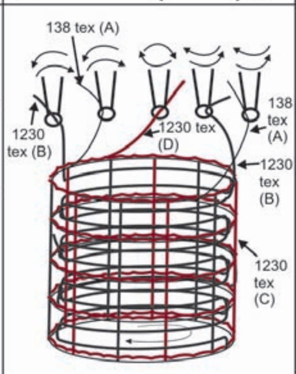
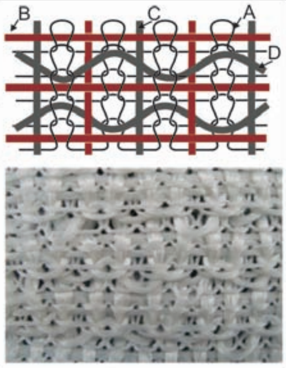
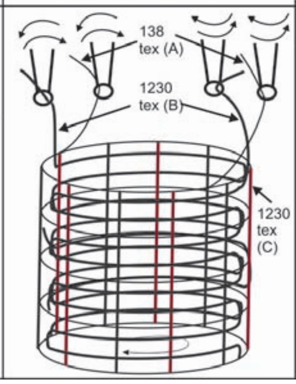
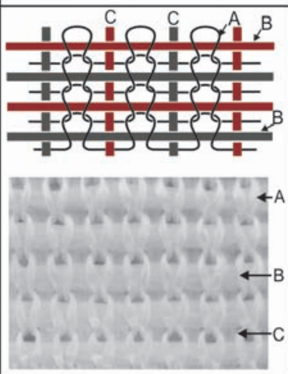
Name	Arrangement of yarns	Schematic of 3D tube construction	2D Knit architecture and fabric structure	Multi-layer 3D tubes
T-WAT	Reinforcement yarns (1230 tex) as warp yarns (C) & tuck stitches (D), and finer yarns (138 tex) as knit loops (A) for base single jersey structure			
T-WWAT	Reinforcement yarns (1230 tex) as warp yarns (C), weft yarns (B) & tuck stitches (D), and finer yarns (138 tex) as knit loops (A) for base single jersey structure			
T-WWA	Reinforcement yarns (1230 tex) as warp yarns (C) & weft yarns (B), and finer yarns (138 tex) as knit loops (A) for base single jersey structure			

Figure 5.21: 3D tubes with integrated reinforcement yarns as warp yarns & tuck stitches (T-WAT), warp yarns & weft yarns as well as tuck stitches (T-WWAT), warp & weft yarns (T-WWA)

for the manufacturing of two fabric layers on both needle beds ensures the joining of all edges of both tubular-structures. In case of tube T-WA, the supplied warp yarns (through open carriage) are integrated in two single jersey knit structures on both needle beds separately using the same finer yarn. The tube T-WAT is knitted following the combined manufacturing techniques of tube T-T and T-WA. The construction of tube T-WWAT is the combination of manufacturing of tubes T-T, T-W and T-WA. In this case, finer and reinforcement weft and warp yarns are used separately for both needle beds. The weft and finar yarns are joined with the respective warp yarns to form two biaxial fabric layers individually on both needle beds. However, one common reinforcement yarn feeder is used in this case to construct the tuck stitches on both needle beds by turns. The consecutive construction of tuck stitch shaped layers on both needle beds using the same reinforcement yarn makes both fabric edges connected to form tubular structure T-WWAT. Conversely, for the manufacturing of tube T-WWA, two biaxial reinforced plane layers are knitted first on both needle beds. Each biaxial plane layer is knitted on respective needle bed using independent reinforcement (weft & warp) and finer yarns. Finally, these two biaxial reinforced plane layers are joined at the edges following rib gatings only on the edge needles of both needle beds using the finer yarn. Thus, a biaxial reinforced 3D tube structure T-WWA is made.

The latest flat knitting technologies for 3D tubes documented above are considered to be the competitive solution and break-through advancements for the manufacturing of 3D tubular structures with flexible fiber-orientation, particularly in the load-directions. The efficient arrangement of high performance yarns in a different way into the knit structures would permit various mechanical performances, likely, high tensile strength, energy absorption, rigidity, etc. Consequently, these high performance 3D tubular structures by means of innovative flat knitting technologies are expected to be promising in high-tech applications.

5.3.6 Development and manufacturing of multi-layered 3D spacer fabrics

Reinforcement of 3D spacer fabrics in multiple layers is essential for high mechanical performances of textile reinforced composites in lightweight applications. At least from 1 to 3 mm wall-thickness of composite, which could be achieved by increasing the fabric specific weights by means of integrating the reinforcement yarns into the fabric structures, is required for the satisfactory reinforcement effects in application. Therefore, innovative flat knitting technologies are developed for the manufacturing of such multi-layered 3D spacer fabrics. These inventive flat knitting technologies for multi-layered 3D spacer fabrics are developed differently for both Aries.3 flat knitting machines considering their available dissimilar spaces between the needle beds (5 mm & 10 mm). Because of the limited distance (5 mm) between the needle beds of conventional Aries.3 machine, maximum two warp sets could be guided through the gap of the needle beds to the knitting zone along with two weft and two loop yarn systems. Consequently, by means of the new technology suitable for the flat knitting machine having limited space between the needle beds (for example, 5 mm), 3D spacer fabrics consisting of multi-layer reinforced plane layers (single weft & single warp inlays) and tuck stitch shaped connecting layers are developed on the conventional Aries.3 flat knitting machine. The developments of these spacer fabrics are carried out on the basis of the innovative knitting technique for consecutive construction of multi-layer as well as tuck stitch shaped structures documented in Figure 5.22. According to this innovative solution, the warp yarns (C) delivered from above and guided by the speciall warp guides [26, 114] to the knitting zone are joined with the weft yarns (B) using the base loop yarn (A) following the single jersey knit pattern. The weft and base loop yarns are guided by

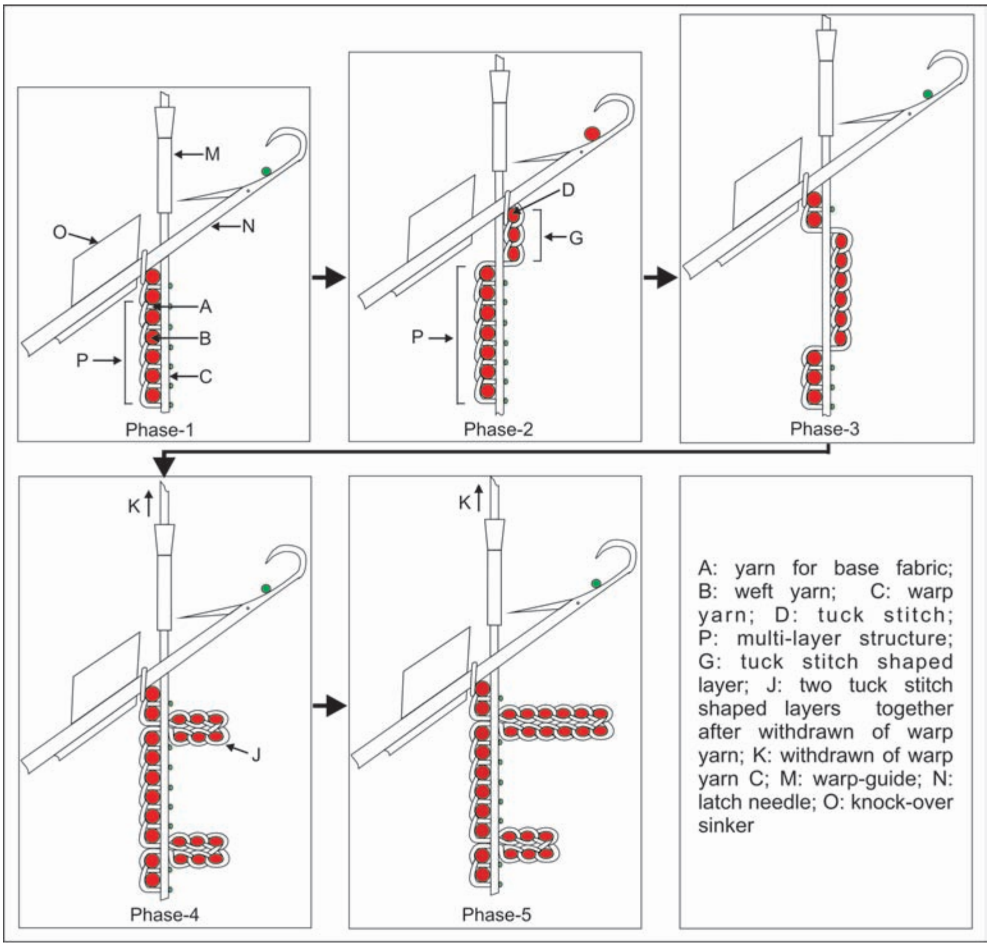


Figure 5.22: Innovative knitting technique for consecutive construction of perpendicularly connected multi-layer and tuck stitch shaped structures

the yarn feeders supplied laterally from the sides of the knitting machine. However, the weft and base loop yarns are positioned at the front and rear side of the warp yarns respectively, if they are counted from the respective needle bed. The warp and weft yarns are arranged as non-crimp yarns in the biaxial directions of the knit pattern (P of Phase-1). Conversely, two independently knitted biaxial reinforced multi-layer structures could be produced at the same time on both needle beds of the flat knitting machine following the aforementioned sequences seperately on both needle beds. By implementing the knitting technique documented in Phase-2, consecutive knit structure (G of Phase-2) independent from the respective warp yarns (C) is able to be produced using the reinforcement and base loop yarns. In this case, the reinforcement yarn supplied (laterally) from the rear side of the respective warp yarns using yarn feeder is integrated only as tuck stitches into the knit structure. Finally, if the warp yarns are drawn back to their free length (Phase-4 & Phase-5), the multi-layer reinforced fabric layer including vertically connected tuck stitch shaped fabric layer (J of Phase-4) would be produced.

5.3.6.1 Multi-layered 3D spacer fabric

For the implementation of new manufacturing technique for multi-layer reinforced 3D spacer fabrics, the Aries.3 (conventional) flat knitting machine is modified (control & construction) at ITM, TU Dresden within the framework of the research program SFB639,A2 of the German Research Foundation [26]. The constructive features are, for instance, the

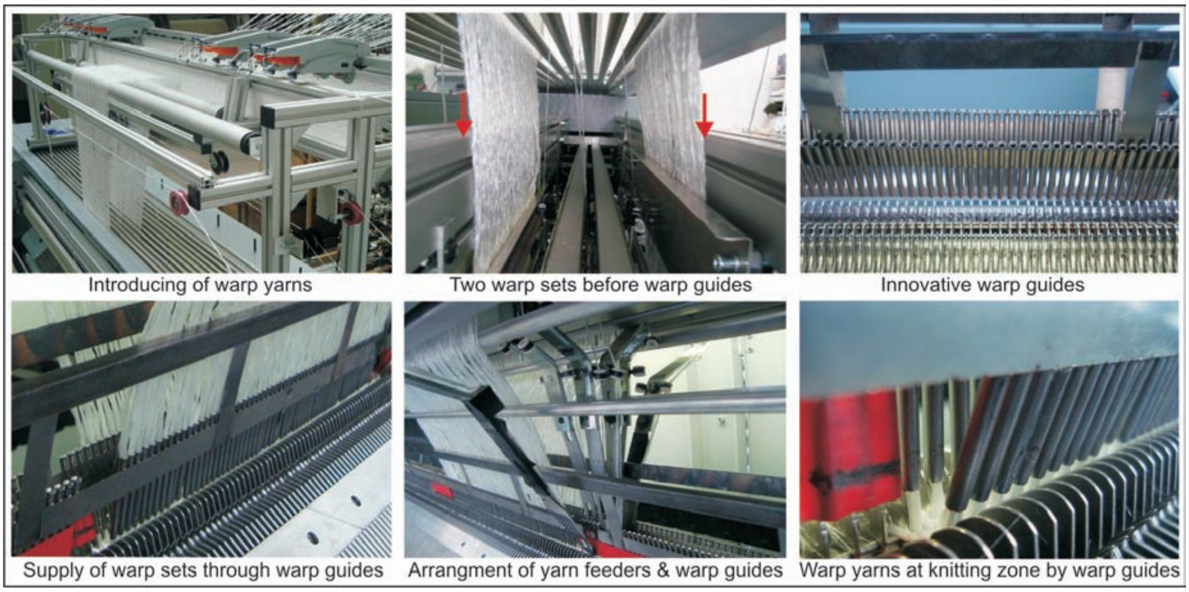


Figure 5.23: Constructive-arrangements of flat knitting machine Aries.3 (conventional) for manufacturing of multi-layered 3D spacer fabrics

new warp delivery system, innovative warp guides, take-down system. The constructive-arrangements of this flat knitting machine are shown in Figure 5.23. The manufacturing principal of multi-layered 3D spacer fabric

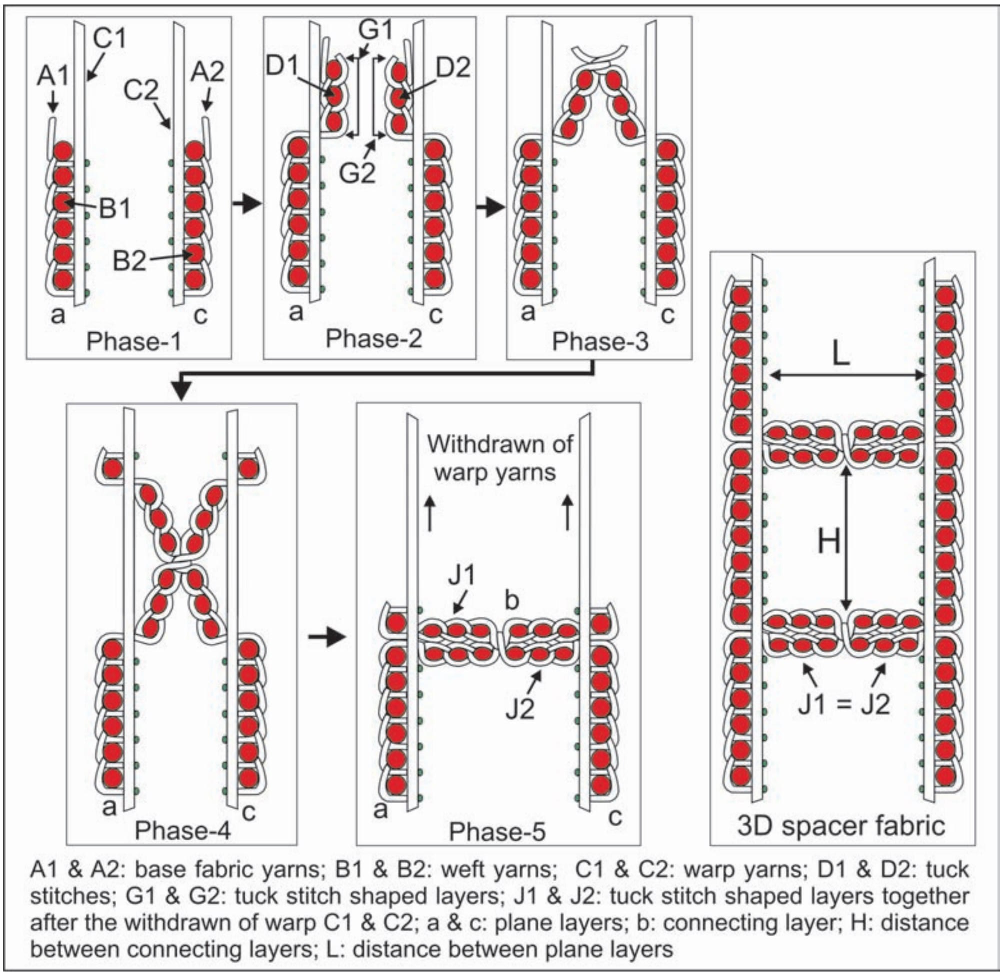


Figure 5.24: Innovative manufacturing technique (schematic) of multi-layered 3D spacer fabric with curvature angle of 0°

with perpendicular connecting layers (spacer fabric type-V or spacer fabric with curvature angle of 0° in the warp direction) is illustrated in Figure 5.24. According to this manufacturing technique, two sets of warp yarns (C1, C2) are delivered individually through the open carriage of the flat knitting machine and guided separately to both needle beds using specially designed warp guides [26, 114]. Two individual weft yarns (B1, B2) are supplied laterally by yarn feeders. These two weft yarns (B1, B2) are joined individually with two warp sets (C1, C2) using two respective base loop yarns (A1, A2) following the knitting technique documented in Figure

5.22 (Phase-1) in order to construct two separate biaxial reinforced plane layers (a, c). Both multi-layer reinforced surface layers are knitted in this case until a pre-designed length of 45 mm is reached. Subsequently, two tuck stitch shaped layers (G1, G2) are knitted individually on both needle beds using the knitting technique documented in Figure 5.22 (Phase-2). Both tuck stitch shaped layers (G1, G2) are knitted to the half length of the pre-designated connecting layer between the plane layers, and then joined together with the base loop yarns (Phases 2-4 of Figure 5.24) and, finally, knitted to the completion. When the warp yarns are drawn back

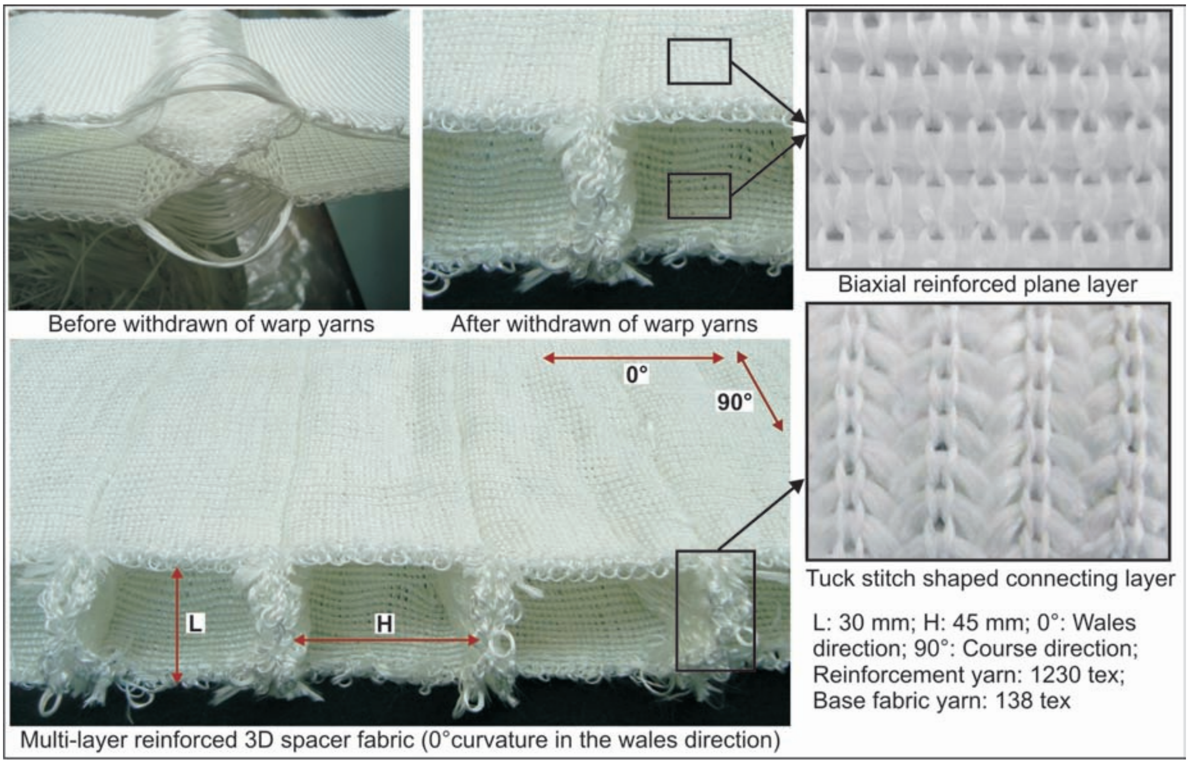


Figure 5.25: Flat knitted multi-layered 3D spacer fabric with curvature of 0° (spacer fabric type-V)

to the length of the pre-designated connecting layer (Phase 5 of Figure 5.24), the combined tuck stitch shaped layers J1 & J2 together as the fabric layer b could perpendicularly connect both biaxial reinforced plane layers. The above mentioned manufacturing sequences are repeated to develop a 3D spacer fabric consisting of multi-layer reinforced plane layers and tuck stitch shaped connecting layers. The successfully manufactured multi-layered 3D spacer fabric is presented in Figure 5.25.

5.3.6.2 Multi-layer reinforced curvilinear 3D spacer fabrics

Curvilinear shaped 3D spacer fabrics are well-suited as textile preforms for curved-shaped composite-structures in lightweight applications leading to high application potential. The manufacturing of curvilinear shaped textile preforms directly by the knitting process would eliminate the discontinuous intermediate processes of conventional textile preforming. Moreover, by this innovative solution, the reinforcement yarns are arranged in the same way to the curving-direction offering high structural benefits especially in high load conditions.

3D spacer fabrics consisting of multi-layer reinforced (as biaxial inlays) plane layers and tuck stitch shaped connecting layers are produced with different curvatures in the warp direction using the innovative manufacturing technique shown in Figure 5.26. Such curvatures are achieved by knitting the variable length of plane layers, while simultaneously knitting the connecting layers on both needle beds. For instance, see knitting Phases 2 to 4 in Figure 5.26, where the tuck stitch shaped layer G1 is longer than G2. These spacer fabrics are shaped curving in the warp direction. This is accomplished by drawing the warp yarns back to their free lengths, which are different for both needle beds. Such curves could be achieved in opposite angles if the tuck stitch shaped layer G2 is knitted longer than G1 in the knitting Phases 2 to 4. Multi-layered 3D spacer fabrics are produced curved in three different pre-designated angles in the warp direction, which are 90°, ±90° and 360°. The spacer fabric with the curvature angle of ±90° is achieved by knitting first of a 90° curvature in

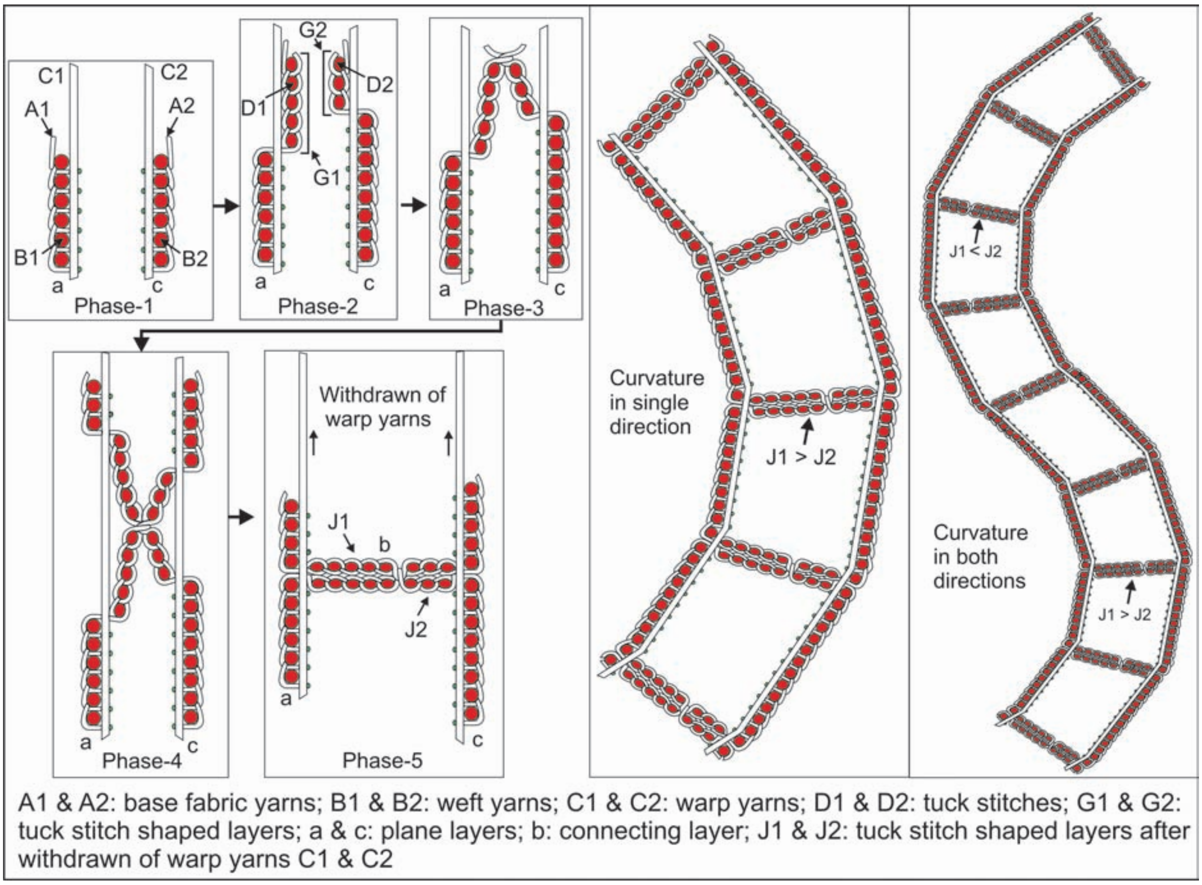


Figure 5.26: Innovative manufacturing technique (schematic) of multi-layer reinfoced curvilinear 3D spacer fabrics (type-Xiii, XiV & XV)

the warp direction, and then curving back to the 0° angle on the very next. Spacer fabrics with 90° and ±90° curvatures are produced by combining both of the manufacturing techniques diagrammed in Figure 5.24 and Figure 5.26, whereas spacer fabric with a 360° curvature is produced using only the manufacturing technique documented in Figure 5.26. The successfully manufactured multi-layer reinforced curvilinear 3D spacer fabrics are presented in Figure 5.27.

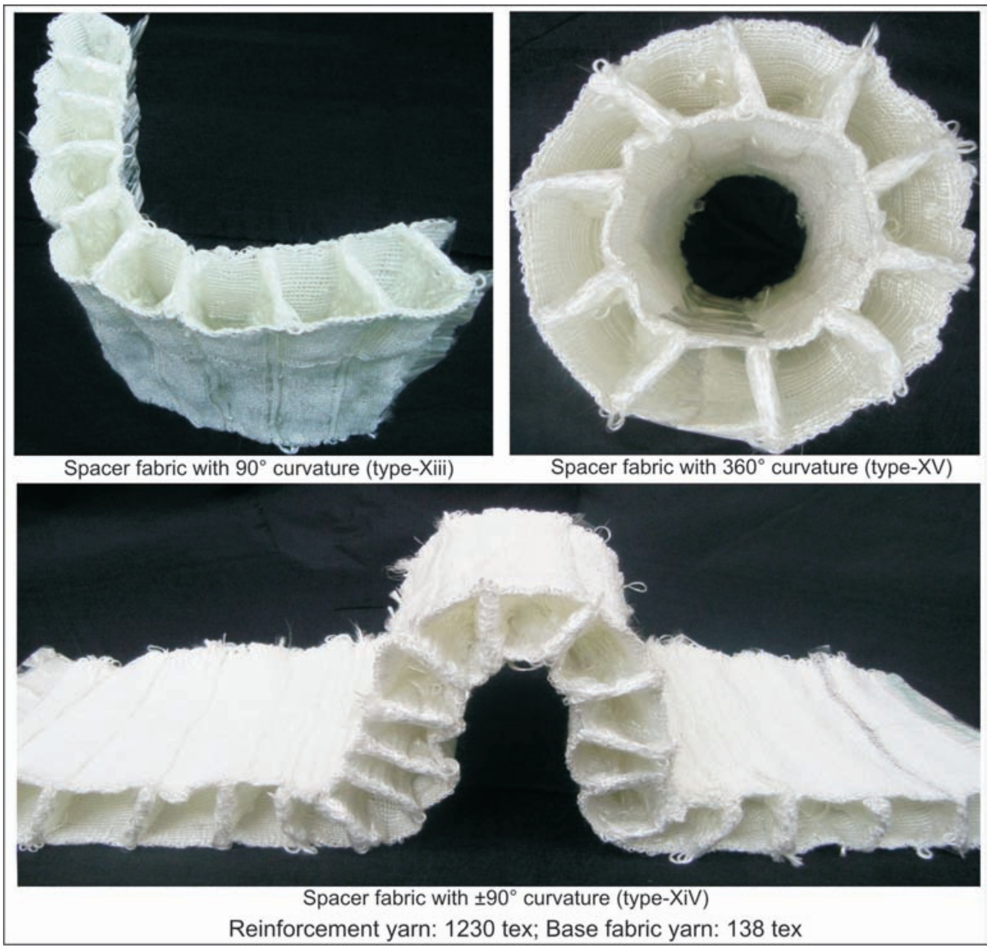


Figure 5.27: Flat knitted multi-layer reinforced curvilinear 3D spacer fabrics (type-Xiii, XiV & XV)

5.3.7 Development and manufacturing of 3D spacer fabrics with 4 reinforcement layers

Multi-layer reinforced 3D spacer fabrics consisting of 4 reinforcement layers into the structures could be produced using the most advanced flat knitting technology developed in this research. In this case, spacious adjustment of needle beds (at least 10 mm) is prerequisite in order to implement such innovative technology, where four warp sets along with four weft and two loop yarn systems are employed together. Such ground-breaking flat knitting technology enables the effortless construction of both plane and connecting fabrics each being made of 4 reinforcement layers (two weft & two warp inlays) leading to increased fabric specific weights (resulting in higher wall thickness of composite). The technological basis of manufacturing such innovative 3D spacer fabrics is illustrated in Figure 5.28. According to this innovative knitting technique, two consecutive

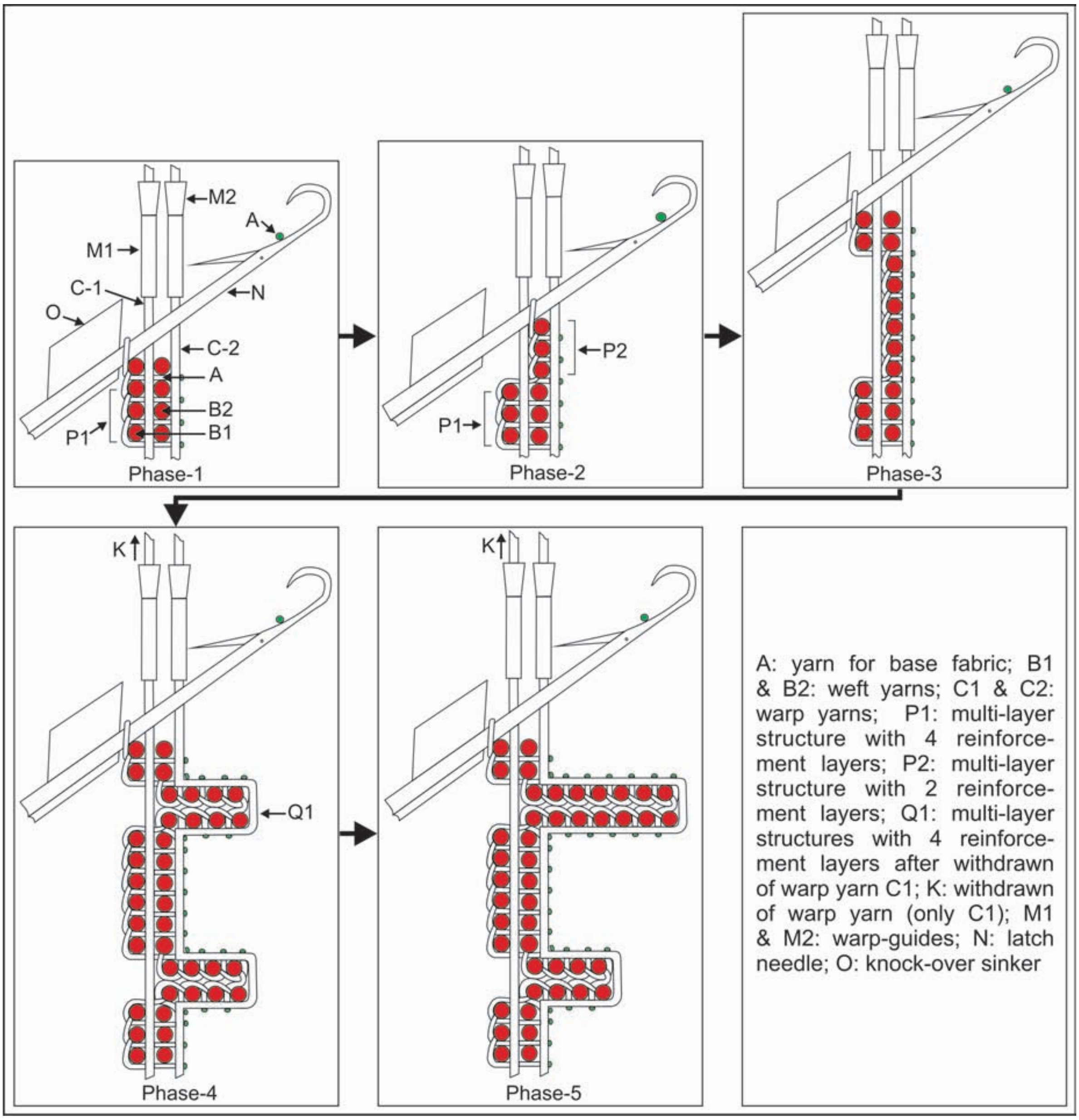


Figure 5.28: Innovative knitting technique for consecutive construction of perpendicularly connected multiple layers (each being made of 4 reinforcement layers)

multi-layer reinforced knit structures, which are produced using the same yarns and comprised individually with 4 reinforcement layers, could be connected perpendicularly and the intermediate layer would hang independently. As it is seen in Figure 5.28, two warp sets (C1 & C2) delivered from above and guided by the specially designed warp guides [26, 114] to the knitting zone are joined with two weft sets (B1 & B2) using the base loop yarn (A) following the single jersey knit pattern. The weft and base loop yarns are guided by the yarn feeders supplied laterally from the sides of the knitting machine. The warp and weft yarns are arranged as non-crimp yarns in the biaxial directions of the knit pattern (P1 of Phase-1). By implementing the knitting technique documented in Phase-2, consecutive multi-layered knit structure (P2 of Phase-2) made of reinforcement warp and weft yarns (B2 & C2) is able to be produced using the same loop yarn (A). In this case, reinforcement weft yarn B1 remains unemployed. Consequently, warp yarn set C1 is not joined within the multi-layered structure P2. Finally, if the warp yarn set C1 is drawn back to its free length (Phase-4 & Phase-5), two consecutive multi-layered structures, which are connected vertically and the intermediate layer is hanged independently, would be shaped.

5.3.7.1 3D spacer fabric with 4 reinforcement layers

The Aries.3 (adavanced) flat knitting machine is used to implement the innovative knitting technique (already documented in Figure 5.28) for manufacturing of 3D spacer fabrics with 4 reinforcement layers. The spacious setting of the needle beds (10 mm distance between both needle beds) allows the knitting with four warp sets along with four weft systems using two base loop yarn systems. However, this machine has also been modified at ITM, TU Dresden [26], for instance, in control and construction, for the manufacturing of innovative 3D spacer fabrics. The Figure 5.29 shows some constructive arrangements of this machine. The manufacturing tech-

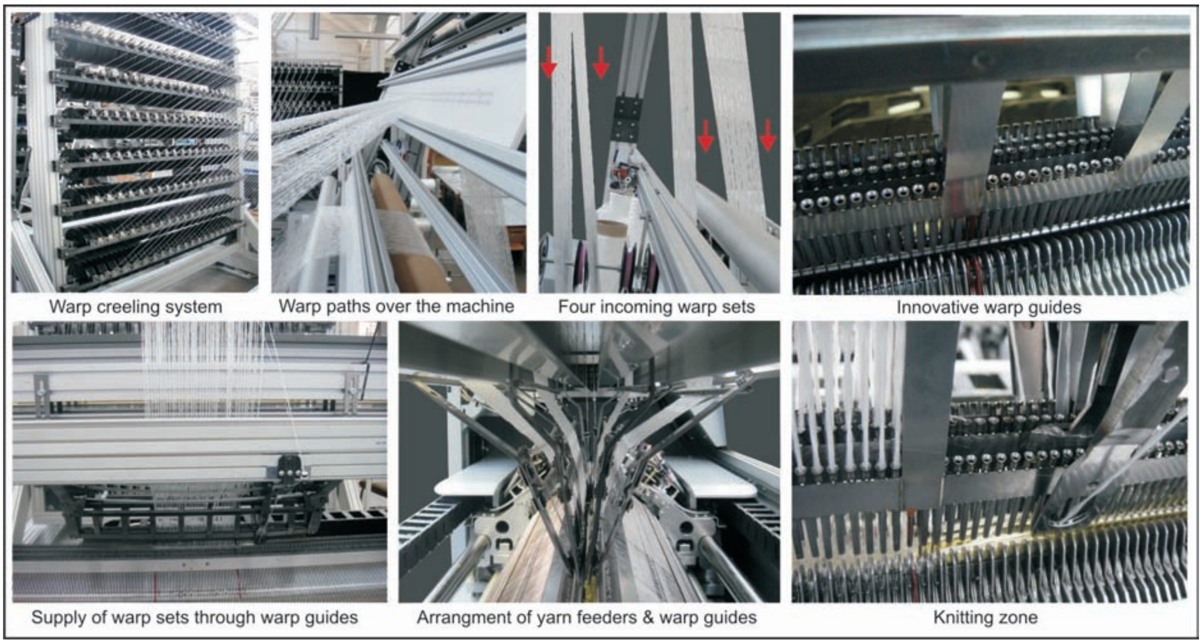


Figure 5.29: Constructive-arrangements of flat knitting machine Aries.3 (advanced) for manufacturing of multi-layer (4) reinforced 3D spacer fabrics

nique of multi-layered 3D spacer fabric with the curvature angle of 0° in the warp direction is documented in Figure 5.30. The manufacturing of this spacer fabric is accomplished as it is described bellow:

- Supply of four different warp sets (C1, C2, C3 & C4 of Figure 5.30) from above to the knitting zone through the open carriage.
- Supply of individual warp sets to the knitting zone by special warp guides [26, 114], whereas two warp sets to each needle bed. For example, warp sets C1 & C2 to the front needle bed and warp sets C3 & C4 to the rear needle bed.
- Four weft yarns (B1, B2, B3 & B4) are supplied laterally by yarn feeders and laid beside the warp sets individually. The weft yarns are positioned before the warp sets if they are counted from the respective needle beds.
- Individual base loop yarns (A1 & A2) are also supplied laterally

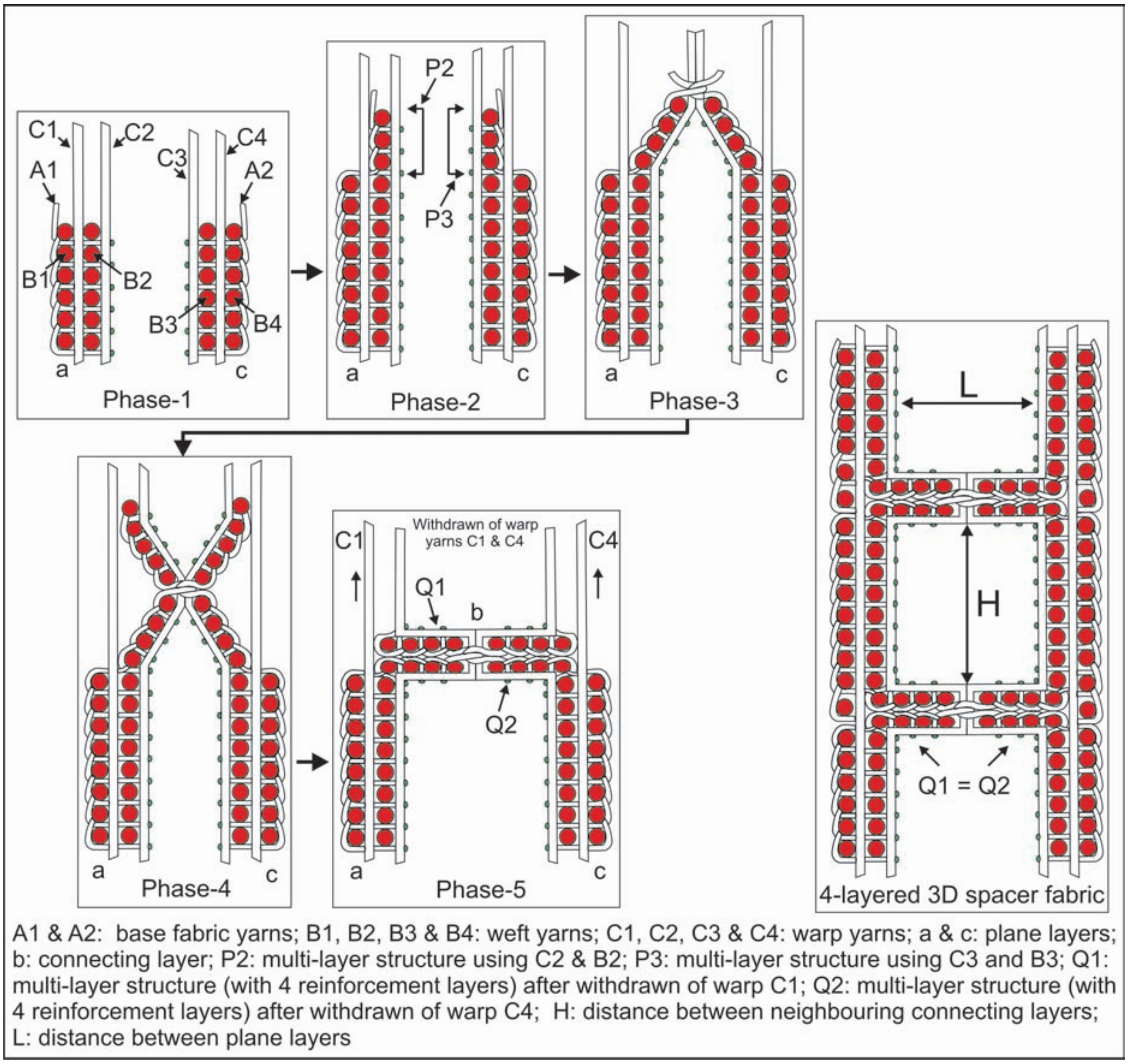


Figure 5.30: Innovative manufacturing technique (schematic) of 3D spacer fabric type-V (curvature angle of 0°) with 4 reinforcement layers

using yarn feeders and are employed to construct two single jersey structures independently on both needle beds. The positions of these loop yarn feeders are set behind all of warp and weft yarns if they are counted from the respective needle beds.

- Warp sets C1 & C2 and weft yarns B1 & B2 are integrated into single jersey structure by the base loop yarn A1 on front needle bed to produce the multi-layered plane fabric a. Similarly, warp sets C3

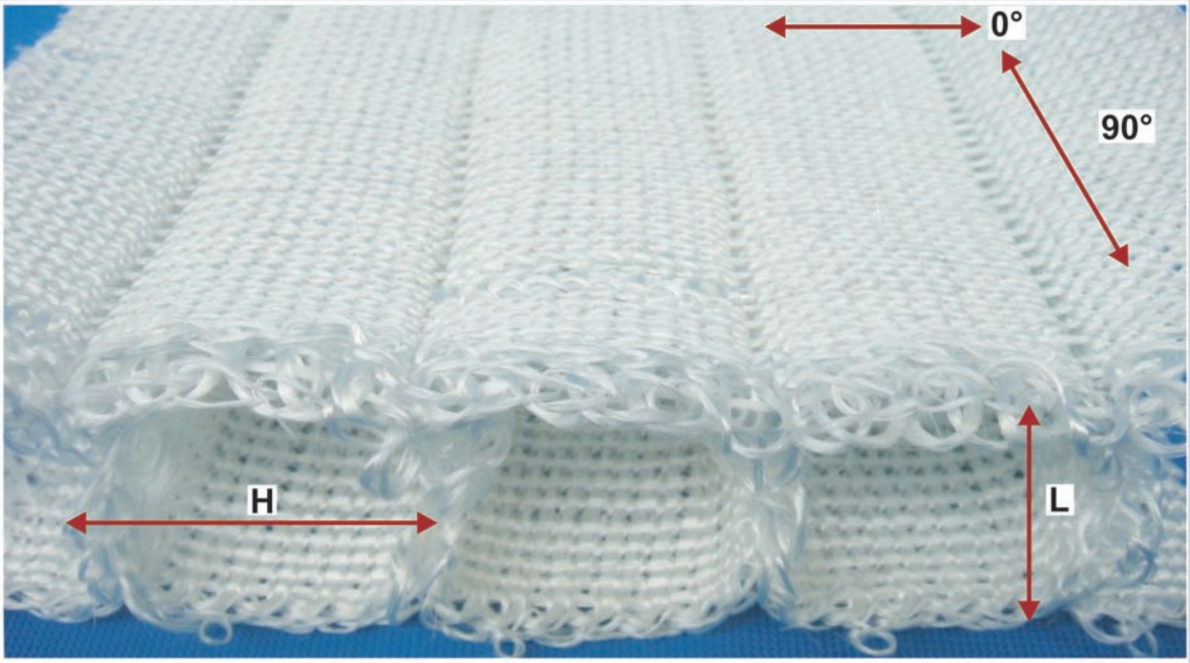
& C4 and weft yarns B3 & B4 are joined by the loop yarn A2 into the single jersey structure on rear needle bed to create the multi-layered plane fabric c independently (Phase-1).

- At the beginning of constructing the connecting layer b, both plane layers a & c are knitted further switching off the weft yarns B1 and B4. Consequently, the warp sets C1 & C4 are remained unemployed within the multi-layered structures on front and rear needle beds respectively. Therefore, two independently knitted multi-layered structures are formed on both needle beds, for example, the structure P2 on front needle bed using warp set C2 along with weft yarn B2 and the structure P3 on rear needle bed using warp set C3 along with weft yarn B3 (Phase-2).

- After knitting the half length of the connecting layer b, both multi-layered structures P2 & P3 are joined together by base loop yarn (Phase-3). Again, both multi-layered structures are knitted individually to the half length of the connecting layer b (Phase-4).

- Finally, when the warp sets C1 & C4 are drawn back to the length of the pre-designated connecting layer b (Phase 5), the multi-layered structures Q1 & Q2 together as the fabric layer b (with 4 reinforcement layers in together) connect both multi-layered reinforced plane layers (a & c) perpendicularly.

- The above mentioned manufacturing sequences are repeated to develop 3D spacer fabric (curvature angle of 0° in the warp direction) consisting of individual fabric layers (plane and connecting layers) each being made of 4 reinforcement layers. The manufactured multi-layered 3D spacer fabric by means of the above mentioned innovative flat knitting technology is documented in Figure 5.31.



3D Spacer fabric with 0° curvature; Reinforcement yarn: 410 tex; Base fabric yarn: 138 tex; H: 45 mm; L: 30 mm; 0°: Wales direction; 90°: Course direction

Figure 5.31: Flat knitted 3D spacer fabric (type-V) with 4 reinforcement layers

5.3.7.2 Curvilinear 3D spacer fabrics with 4 reinforcement layers

The innovative flat knitting technique for 3D spacer fabrics with four reinforcement layers also permits the manufacturing of 3D spacer fabrics in curvilinear shapes. The manufacturing technique for curvilinear 3D spacer fabrics with 4 reinforcement layers is presented in Figure 5.32. The basis of manufacturing two plane layers as well as consecutive connecting layers at a time independently on both needle beds are as same as they are for the manufacturing of 3D spacer fabric with curvature angle of 0° documented in Figure 5.30. However, the curvilinear shapes (in the warp direction) are achieved by knitting the variable lengths of plane layers while simultaneously knitting the connecting layers on both needle beds (Phase 2 to 4 in Figure 5.32). For example, the multi-layered structure P2 is knitted longer then the structure P3 in order to get the curvature in the clockwise direction. Again, the curvature in the opposite angle

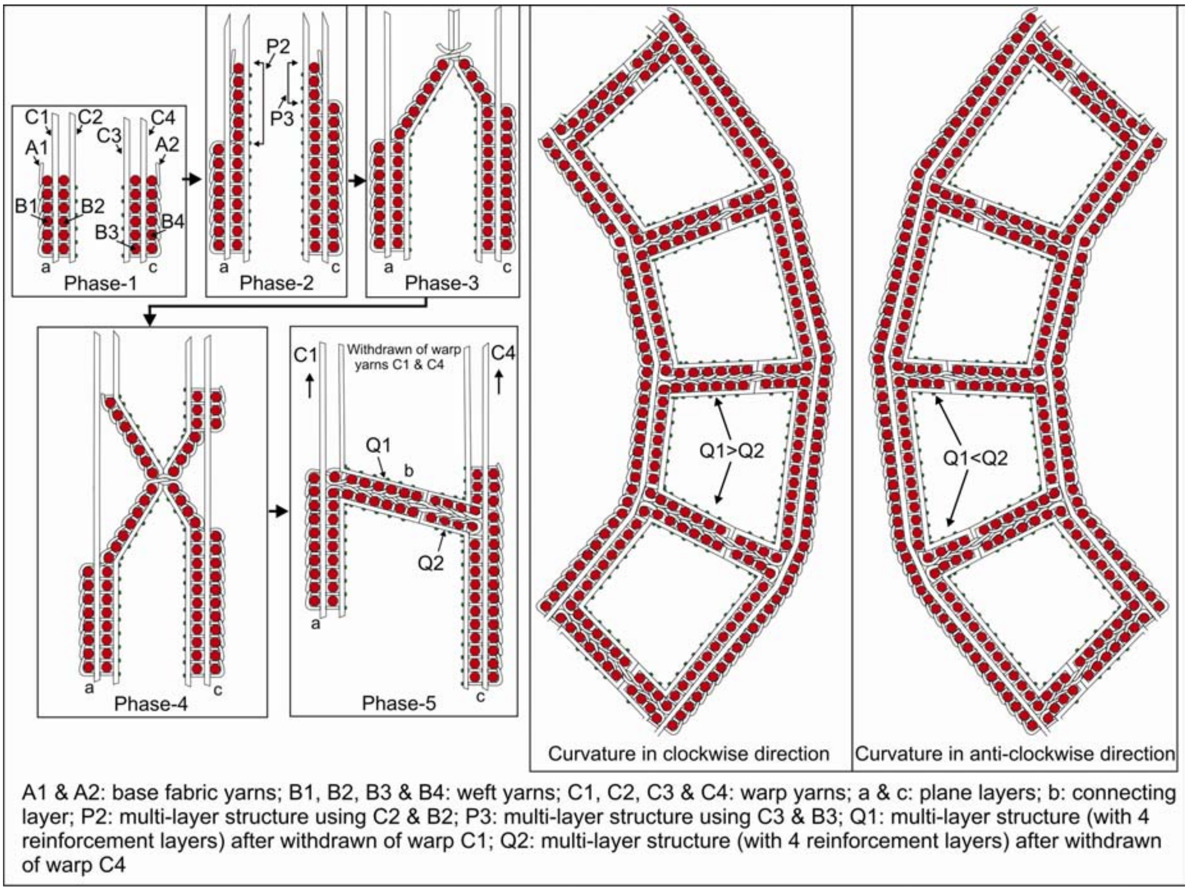


Figure 5.32: Innovative manufacturing technique (schematic) of curvilinear 3D spacer fabrics with 4 reinforcement layers

(anti-clockwise direction) could be achieved if the multi-layered structure P3 is knitted longer than P2. The multi-layered 3D spacer fabrics are accomplished into curvilinear-shapes by drawing the surface warp yarns C1 & C4 (Phase-4) back to their free lengths, which are unlike for both plane layers. However, multi-layered 3D spacer fabrics are produced as curved in two different pre-designated angles (90° and 360°) in the warp direction. The successfully knitted curvilinear 3D spacer fabrics with 4 reinforcement layers are presented in Figure 5.33.

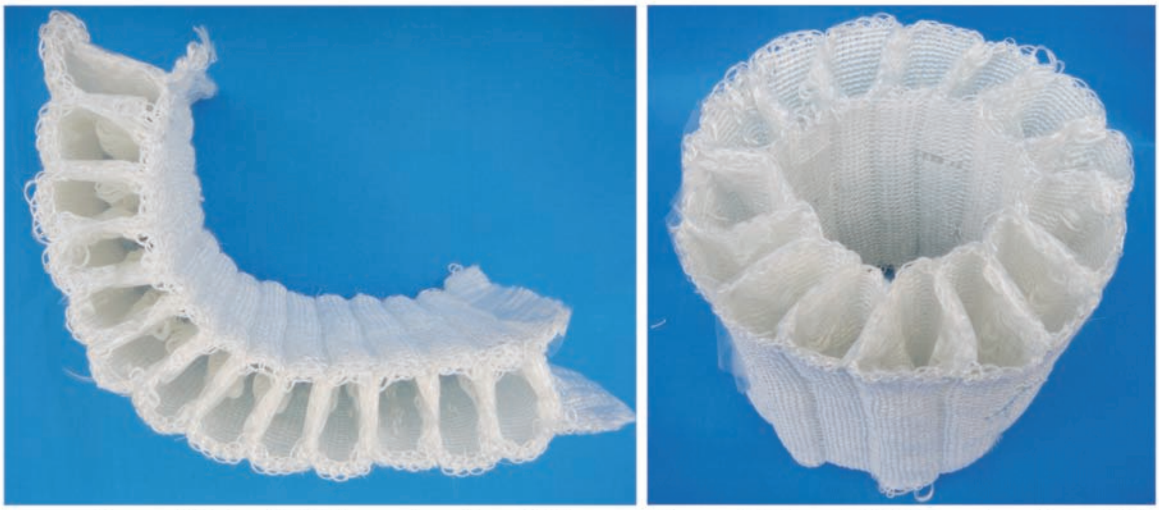


Figure 5.33: Flat knitted curvilinear 3D spacer fabrics (type-Xiii & XV) with 4 reinforcement layers

5.3.8 Integration of "sensor-network" (functional yarn) for structural health monitoring

"Sensor-networks" created within the textile preforms using various functional/ conductive-materials could be used to monitor the structural-health of end products. The effortless integration and creation of such "sensor-networks" within the fabric structures at the same time while manufacturing the multi-layered 3D spacer fabrics is considered to be the break-through advancement in fully-automated manufacturing of function-integrated textile preforms. This new technology would minimize the additional intermediate processes leading to low manufacturing cost. However, functional yarns are integrated successfully as weft yarns into multi-layered knit structures using the developed integration method illustrated in Figure 5.34. This technique is implemented on the Aries.3 (advanced) flat knitting machine. In this method, functional yarn is guided by an additional yarn feeder along with the other yarn feeders for rein-

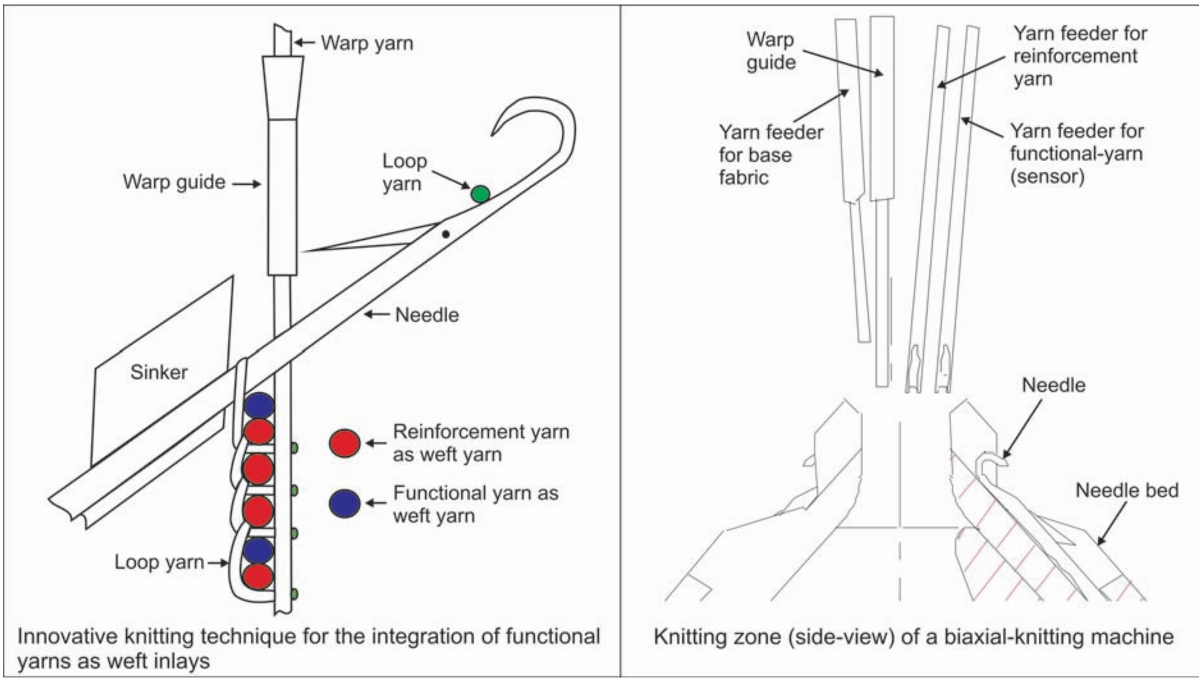


Figure 5.34: Schematic knitting technique and knitting zone for the creation of "sensor-network" in multi-layered knit structure

forcement and finer base fabric yarns, whereas the warp yarns are supplied by the warp guides. Both reinforcement and functional yarns are supplied from the front side of the warp yarns, if they are counted from their respective needle bed. These reinforcement and functional yarns are placed between the respective warp set and needle bed, when these yarn feeders are driven together to the knitting zone in knitting process. On the very next, the needles are raised over the functional and reinforcement yarns and passed through the warps to receive the finer base fabric yarn from the back side of the warp set. This finer yarn is used to construct the single jersey knit structure. Consequently, both functional, reinforcement and warp yarns are placed in multi-layers (biaxial-orientation) within the single jersey knit structure. The functional yarn could be integrated into knit structure using both conventional and intarsia yarn feeders. In this experiment, the functional yarns are integrated using only the conventional yarn feeders. The schematic paths of yarn feeders (conventional)

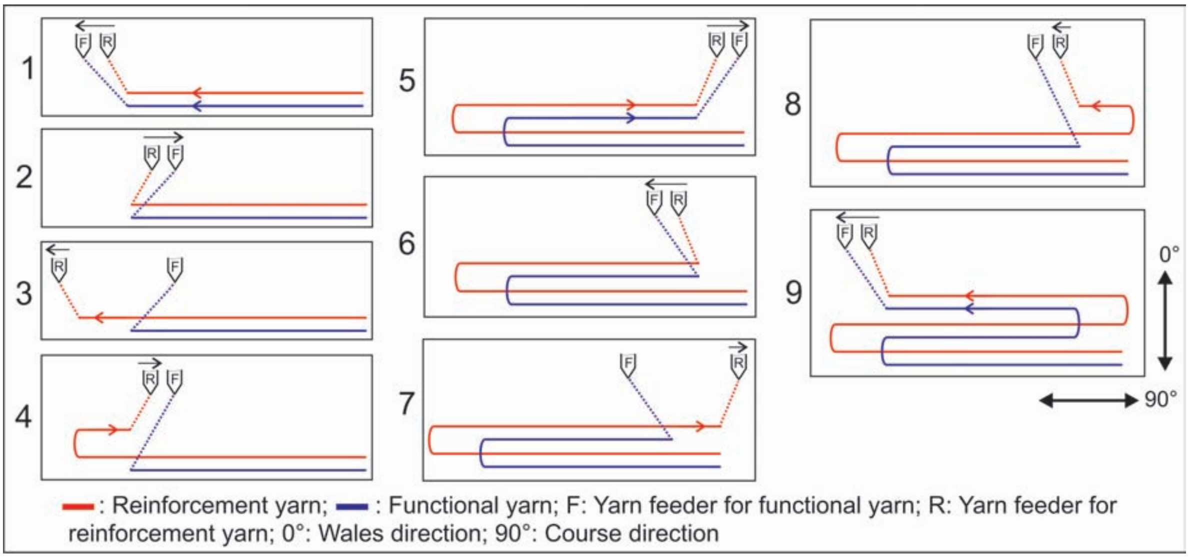


Figure 5.35: Example of schematic paths of yarn feeders (conventional) in integration of "sensor-network" into multi-layered knit structure

in the integration of "sensor-network" into multi-layered knit structure are illustrated as an example in Figure 5.35. The developed solution offers the possibility of integration various functional materials in different forms, for instance, carbon filaments, metallic-wires (copper, steel, etc.), optical fibres, core-wrapped yarns from different material-combinations. Moreover, this technology-system is considered to be the most flexible in designing of "sensor-networks" within knit-structures. On the other hand, sensor-yarn could be easily integrated as warp yarn within multi-layered knit structure, just combining a functional yarn together with the reinforcement warp yarn. The "sensor-networks" are created successfully into 2D knit structures as well as multi-layered reinforced (4 reinforcement layers) 3D spacer fabrics through single-step manufacturing process using the developed technology-system described above. These fabrics are presented in Figures 5.36 and 5.37.

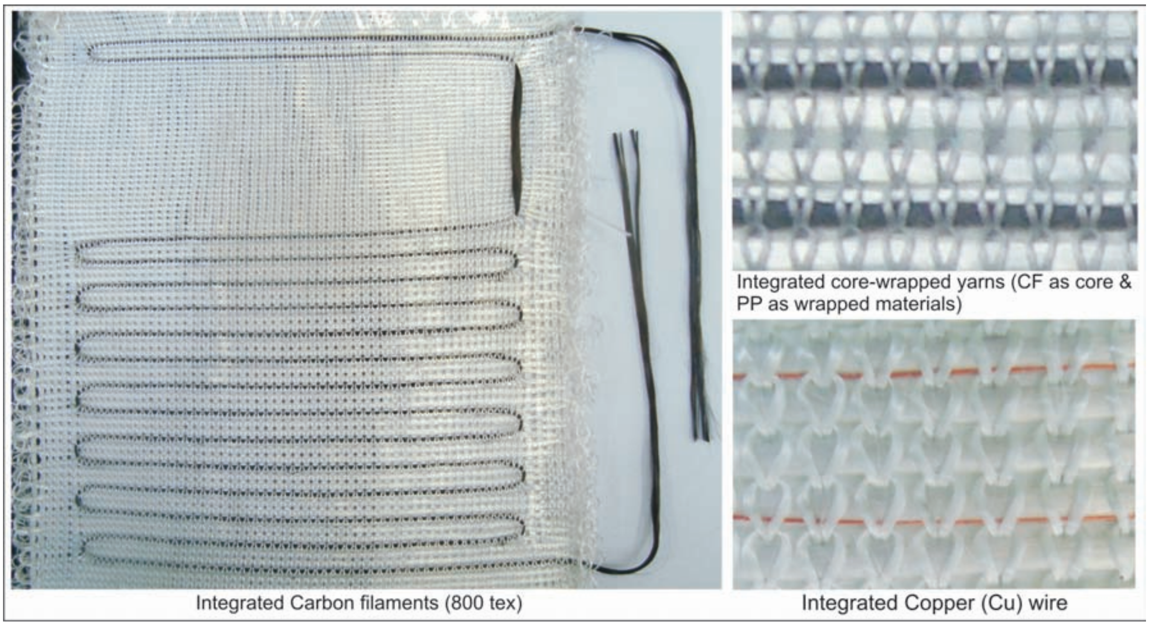


Figure 5.36: Multi-layer reinforced 2D knit fabrics with integrated "sensor-networks" for structural health monitoring

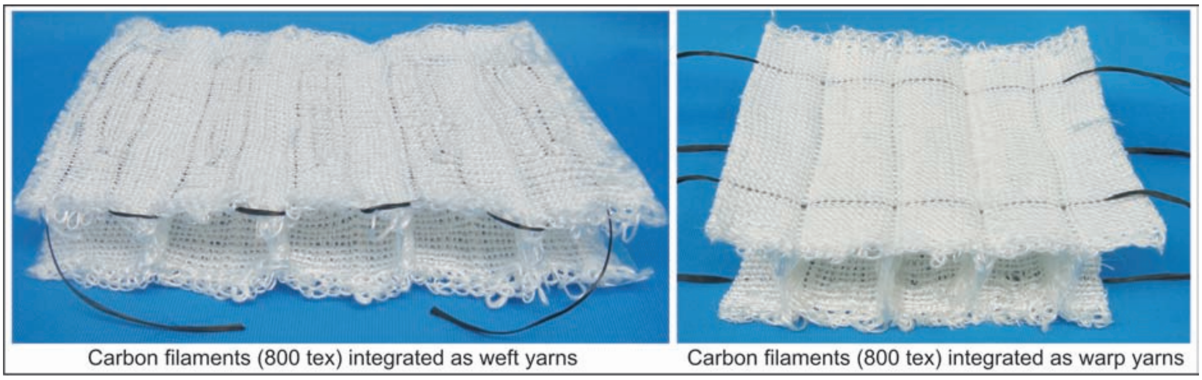


Figure 5.37: Multi-layer reinforced (4 layers) 3D spacer fabrics with integrated "sensor-networks" for structural health monitoring

5.3.9 Thermoplastic consolidation of 3D spacer fabrics into composites

To fabricate 3D composite, the laboratory hot-pressing machine (COLLIN P300 PV, Dr. Collin GmbH, Germany) at ITM, TU Dresden is used to process the flat knitted 3D spacer fabric (size: 18 cm x 23 cm). Specially designed mechanical tools [26,115] developed at Institute of Solid Mechanics (IFKM) of TU Dresden, which are developed only for the consolidation of spacer fabric type-V (with 0° curvature in the wales direction), are used for the thermoplastic moulding process. A big-seized weft reinforced 3D spacer fabric (size: 90 cm x 90 cm) is also consolidated at the Institute of Lightweight Engineering and Plastic Technology (ILK) of TU Dresden. High temperature and high pressure are used to consolidate 3D spacer fabrics into 3D composites. At first, spacer fabric is put into the press

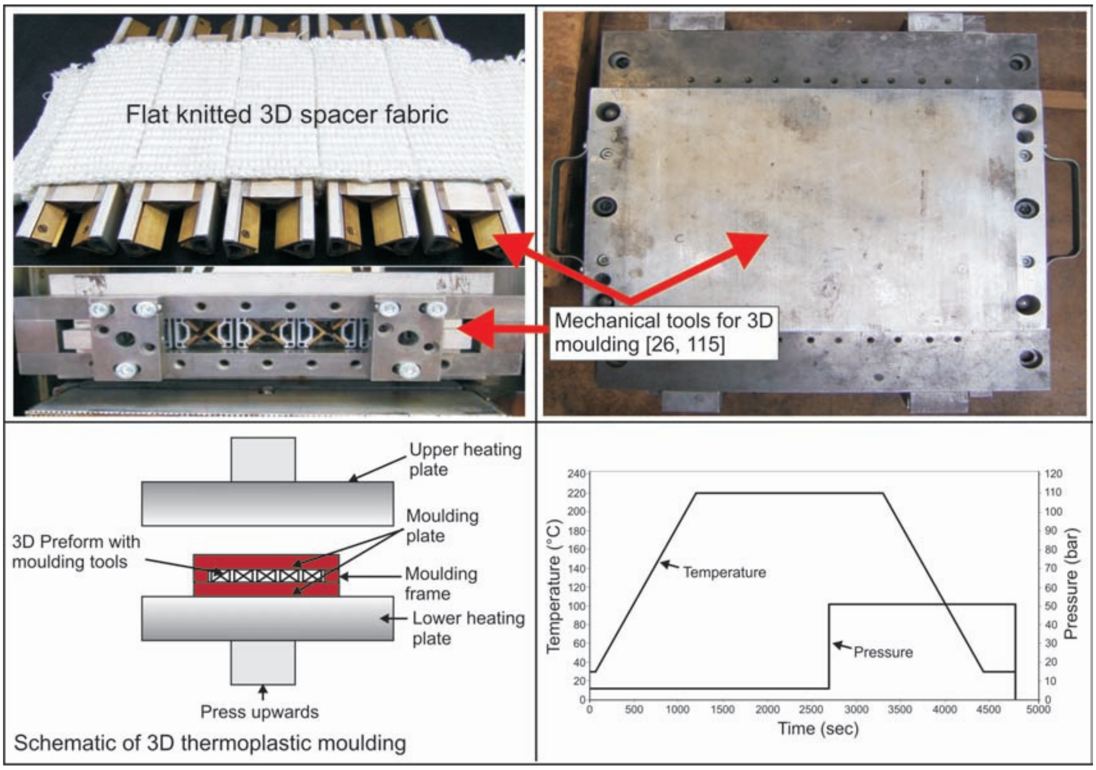


Figure 5.38: Thermoplastic consolidation of 3D spacer fabric into composite at laboratory hot-pressing machine (ITM, TU Dresden)

at room temperature and an initial pressure of 6 bars is applied. The temperature is then raised at the rate of 10°C per minute until 221°C is reached for the melting of the polypropylene. After 25 minutes at 221°C a pressure of 51 bars is applied (suddenly increased) and this temperature is kept for 10 minutes. Finally, the temperature is dropped down (approximately at the rate of 8°C per minute) to room temperature keeping the pressure constant. Temperature and pressure flowcharts, along with the used mechanical tools for 3D moulding have been shown in Figure 5.38. The consolidated thermoplastic composites using flat knitted weft reinforced 3D spacer fabrics are shown in Figure 5.39.

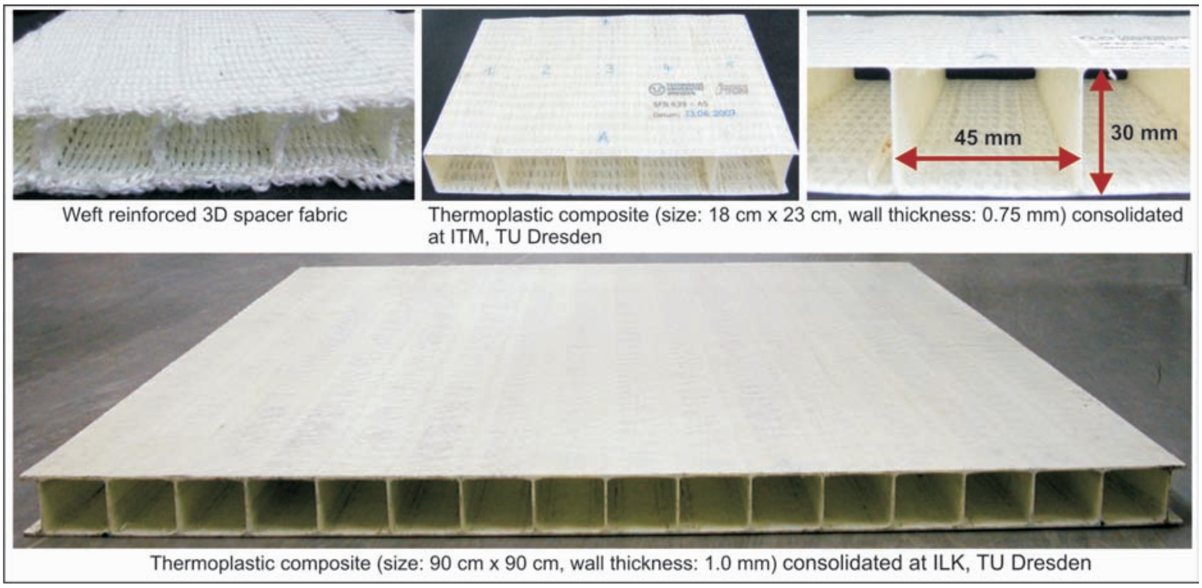


Figure 5.39: Rigid panel-structures (composites) using flat knitted weft reinforced 3D spacer fabrics

Thermoplastic consolidation of 3D spacer fabric is carried out by single processing stage applying high temperature and pressure. The homogeneous mixing of thermoplastic matrix component (PP) together with the reinforcing component (GF) in the formation of hybrid yarn enables the effortless thermoplastic consolidation from fabric to composite. This consolidation process would be integrated into the fully automatic process-chain from preforms to the finished composites in the Collaborative Research Project SFB639 [26]. The further aim of the research project is to limit the total consolidation process within only few minutes, which would be in together the ground-breaking advancement for composite industries for manufacturing of the complex shaped high performance composites economically in industrial scales.

Chapter 6

Analysis of mechanical properties of spacer fabrics

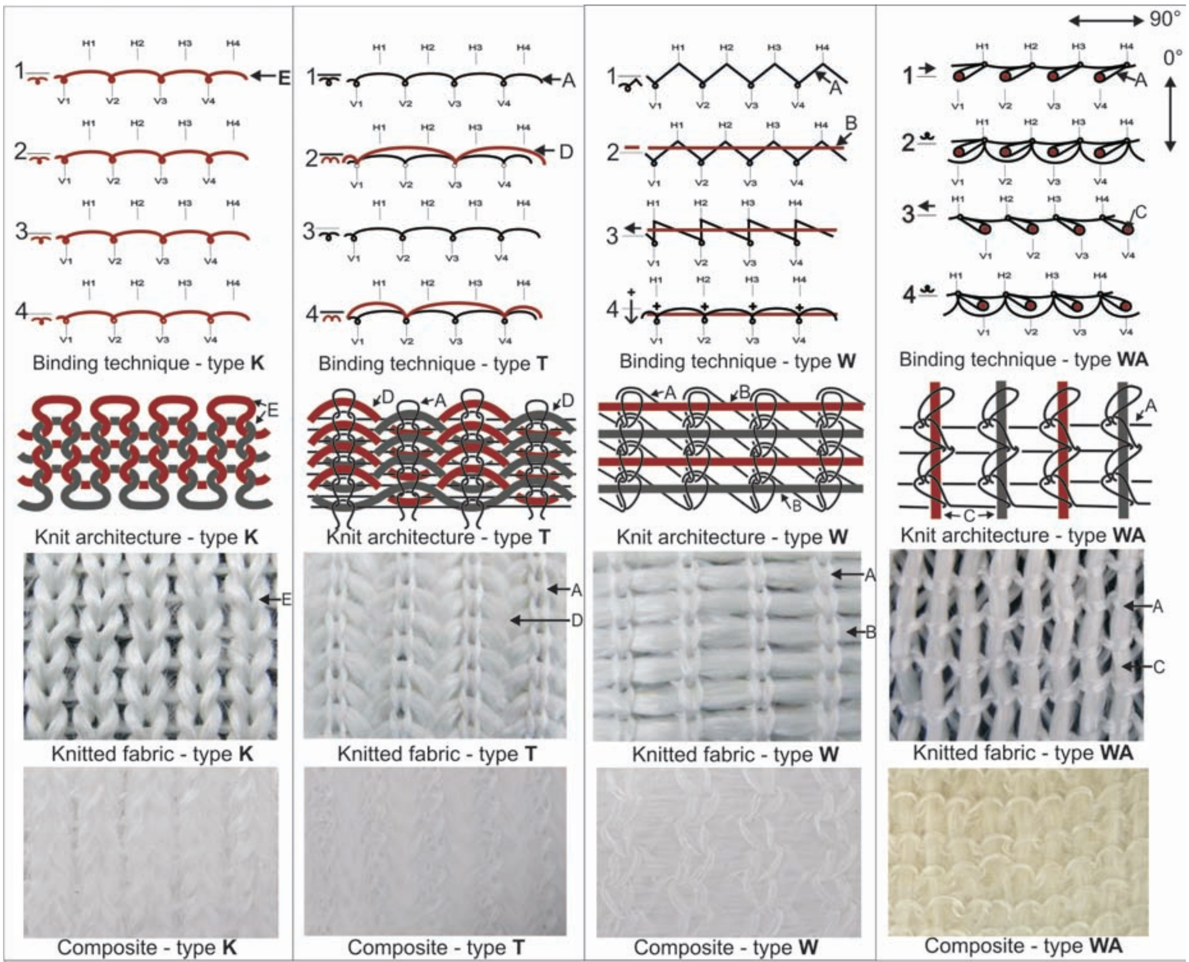
Innovative 3D spacer fabrics are developed successfully including the reinforcement hybrid yarns integrated as weft and warp inlays (as multiple layers) for high mechanical performances, especially for the application as 3D complex shaped textile preforms in high performance composites. However, the reinforcement hybrid yarns could also be integrated into the knit structures separately as knit loops, tuck stitches, weft yarns and warp yarns or combinations of them using the innovative knitting techniques (integration concepts) already discussed in the section 5.3.3. These integration techniques are developed in order not only to check the possibility of integration of reinforcement yarns by flat knitting, but also to investigate the effect of fiber orientations on the mechanical properties of yarns, fabrics and composites. Since the mechanical properties of 2D knit fabrics are considered to be the reflectors of the mechanical properties of individual fabric layers of 3D spacer fabrics (if both the fabrics produced are same), further investigations are carried out on the 2D knit fabrics. The aim of such investigations is to study the effect of different integration (arrangement) of reinforcement yarns on the tensile properties of GF-PP hybrid yarns, 2D knit fabrics and on the mechanical properties of 2D knit composites. These investigations are presented in following subsections.

6.1 Effect of different integration techniques of reinforcement yarns on the tensile properties of GF-PP hybrid yarns and 2D knit fabrics

2D knit fabrics are produced individually with the reinforcement yarns (1230 tex GF-PP hybrid yarns) integrated in the fabric structures as knit loops (K), tuck stitches (T), weft yarns (W), warp yarns (WA) and as weft and warp yarns (WWA) in order to analyse the effect of different integration techniques (different arrangement of reinforcement yarns) on the tensile properties of GF-PP hybrid yarns and 2D knit fabrics. The integration techniques are followed as they are discussed in the section 5.3.3. Moreover, the manufacturing and fabric details of these 2D knit fabrics are illustrated in Figures 6.1 & 6.2 and in Table 6.1.

6.1.1 Tensile testing of reinforcement yarns and 2D knit fabrics

The tensile strengths of 1230 tex GF-PP hybrid yarns and 2D knit fabrics are measured on the Zwick Z100 testing machine (Zwick GmbH & Co. KG, Germany) at ITM, TU Dresden. The method used for assessing the degradation of tensile strength of reinforcement GF-PP hybrid yarns is based on measuring the strength before (T_{bk}) and after knitting (T_{ak}), and calculating their strength loss (Δ_k) as a percentage according to the following formula:



Type **K**: Reinforcement yarn as knit loop; **T**: as tuck stitch; **W**: as weft yarn; **WA**: as warp yarn; A: Yarn for base fabric structure; B: Reinforcement yarn as weft yarn; C: as warp yarn; D: as tuck stitch; E: as knit loop; H: Needles of rear needle bed; V: Needles of front needle bed; →Knit loop on front needle bed; →Knit loop on rear needle bed; →Tuck stitch; →Knit loop on front needle bed and tuck stitch on rear needle bed; →Racking of rear needle bed from right to left direction; →Feeding of reinforcement weft yarn; →Feeding of weft yarn and knit loop with the base loop yarn on very next; →Loop transfer from rear needle bed to front needle bed; 0°: wales direction; 90°: course direction

Figure 6.1: Knitting technique, knit architecture, knit fabric and composite of different integration techniques of reinforcement yarns (e.g. knit loops, tuck stitches, weft yarns, warp yarns)

$$\Delta_k\% = \frac{(T_{bk} - T_{ak})}{T_{bk}} \times 100 \tag{6.1}$$

The measurement of the yarn breaking force after knitting could be measured after carefully unravelling the yarns from the knit fabrics. The tensile strengths of the yarns are measured following test standard DIN EN ISO 2062, where a mesuring length is 50 cm. On the other hand, 2D knit

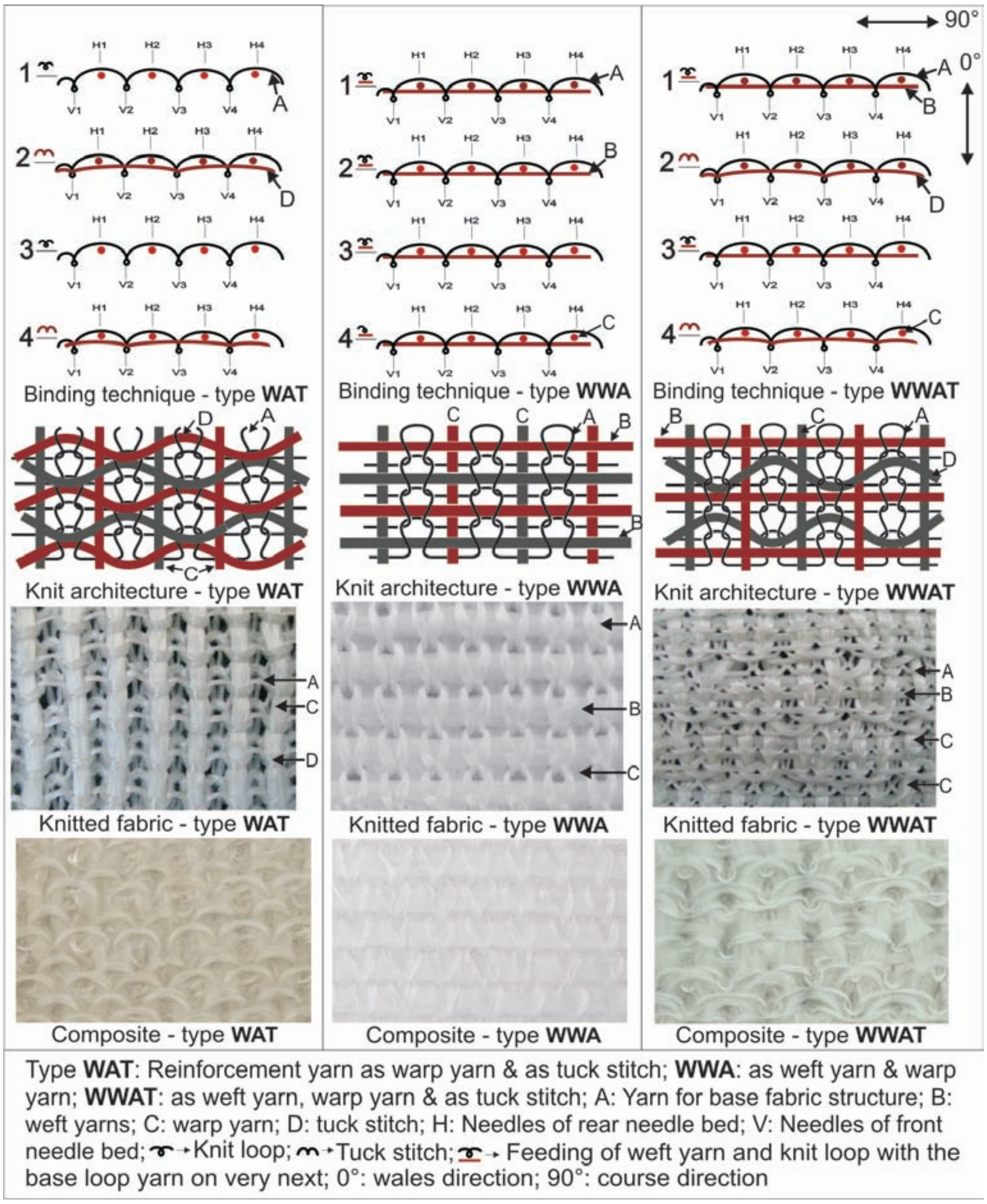


Figure 6.2: Knitting technique, knit architecture, knit fabric and composite of different integration techniques of reinforcement yarns (e.g. warp yarns & tuck stitches; weft yarns & warp yarns; weft & warp yarns and tuck stitches)

fabrics are used to measure the tensile properties according to the test standard DIN EN ISO 13934-1 (size of test specimen: 20 cm in length and 5 cm in width).

Type	Fabric specifications					Composite thickness (mm)	Volume of GF in composite (%)
	Wales/ cm	Course/ cm	Loop length (cm)	Weight (kg/m^2)	Fabric thickness (mm)		
K	1.90	2.50	1.30	1.20	1.80	0.75	52.50
T	1.00	4.10	1.90	1.30	2.00	0.81	45.20
W	1.00	3.80	1.80	0.90	1.50	0.62	44.33
WA	2.60	3.60	1.27	0.60	0.90	0.41	40.05
WAT	2.20	2.50	1.65	0.80	1.20	0.50	44.46
WWA	2.80	2.70	1.32	0.80	1.20	0.50	46.08
WWAT	2.10	2.80	1.22	0.70	1.10	0.45	44.31

Table 6.1: Details of 2D knit fabrics and 2D knit composites

6.1.2 Tensile properties of reinforcement yarns and 2D knit fabrics

Different techniques for the integration of reinforcement yarns into 2D knit structures have a clear effect on the tensile properties of the hybrid yarns. The tensile strength of 1230 tex reinforcement GF-PP hybrid yarn (original) is measured to be 307.6 N per mm^2 (9.76 cN/tex). The stress-strain curves of reinforcement yarns are presented in Figure 6.3 (a), whereas Figure 6.3 (b) illustrates the degradation of tensile strengths of reinforcement yarns due to their different arrangements in the knitted structures. The maximum loss of yarn strength is recorded about 70 % for knit loops and about 45 % for that of tuck stitches, but no more than 5-10 % for biaxial inlays (warp and weft yarns). Consequently, knit fabric with reinforcement yarns as biaxial inlays shows improved tensile properties with equally reduced elongation in both course and wales directions. However,

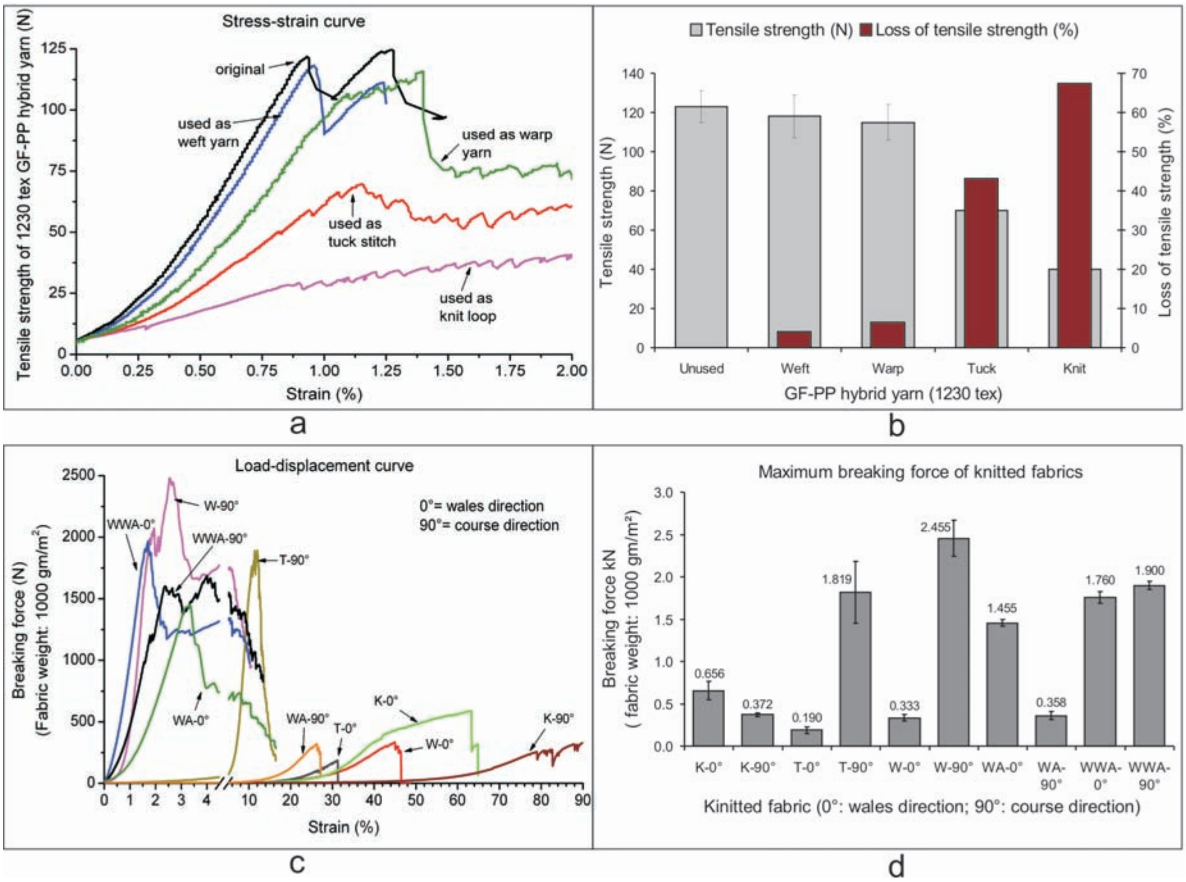


Figure 6.3: Influence of yarn arrangements on the tensile strengths of GF-PP reinforcement yarns (a & b) and 2D knit fabrics (c & d)

these properties are at their maximum in the course direction for weft yarns (c & d of Figure 6.3). Conversely, knit fabric with reinforcement yarns integrated only as warp yarns shows in the course direction the same tendency of tensile properties of the knit fabrics with biaxial inlays (warp and weft inlays). Nevertheless, the unlike number of course/cm and wales/cm of reinforcement yarns causes to the dissimilar levels of tensile properties in the respective reinforcement directions of the knit fabrics with reinforcement yarns as weft yarns, warp yarns and as biaxial inlays. On the other hand, knit fabrics with tuck stitches also have improved tensile strength in the course direction similar to biaxial inlays. However such tensile strength is recorded after a considerable amount of elongation before breaking. In the case of reinforcement hybrid yarns, about 45 %

less tensile strength is recorded when they are used as tuck stitches rather than as biaxial inlays. Even though the reinforcement yarns are orientated as tuck stitches (curved) into the fabric, the tensile strength of the knit fabric in the wales direction is found to be very inferior, approxiamately 10 % that of the course direction. It can be inferred, that glass filaments of reinforcing yarns, which are brittle upon bending, are damaged mostly when used for knit looping. On the other hand, such damage of glass filament is moderate with tuck stitching, where the curvilinear shaping of reinforcement yarns are not so high. However, warp and weft yarns as biaxial inlays (multiple layers) are not involved in the loop forming operation and are only placed as floated yarns into the knit structures. This result is also supported by the effect of the maximum orientation of reinforcing yarns in course and wales directions as biaxial inlays (non-crimp yarns).

6.2 Effect of dissimilar integration of reinforcement yarns on the mechanical properties of 2D knit composites

In order to investigate the effect of different arrangement of reinforcement yarns (by dissimilar integration methods) on the mechanical properties of 2D knit composites, seven knit structures with different arrangement of reinforcement yarns into the structures are knitted seperately. These knit structures are: 2D knit structures with the reinforcement yarns integrated as as knit loops (K), tuck stitches (T), weft yarns (W), Warp yarns (WA),warp yarns and tuck stitches (WAT), warp and weft yarns (WWA) and warp & weft yarns along with tuck stitches (WWAT). The 1230 tex GF-PP hybrid yarns are used to reinforce all knitted structures.

However, the knit structures K, W and T are produced on the flat knitting machine Stoll CMS 320 TC, whereas the knit structures WA, WAT, WWA and WWAT are manufactured on Aries.3 (modified: first version) flat knitting machine. The reinforcement yarns are integrated into the fabric structures K, T, W, WA and WWA using the innovative integration concepts described in section 5.3.3. Additionally, fabric structures WAT and WWAT are knitted combining the reinforcement-integration concept “tuck stitches” with the concepts “warp yarns” and “warp and weft yarns” individually. The manufacturing and fabric details of these 2D knit fabrics are already illustrated in Figures 6.1 & 6.2 and in Table 6.1.

6.2.1 Measuring the mechanical properties of 2D knit composites

Composites are produced from knit fabrics on the laboratory hot-pressing machine (COLLIN P300 PV, Dr. Collin GmbH, Germany) at ITM, TU Dresden. Temperature and pressure flowcharts, along with the used mechanical tools for 2D moulding are shown in Figure 6.4. At first, knit fabrics are put into the press at room temperature and the pressure is applied to 9 bars. The temperature is then raised at the rate of 10°C per minute until 221°C is reached for the melting of the polypropylene. After 6 minutes at 221°C a pressure of 52 bars is applied (suddenly increased) and these temperature and pressure are kept for 10 minutes. Finally, the temperature is dropped down to room temperature keeping the pressure constant. Tensile and flexural testing is performed on Zwick Z100 strength testing machine at ITM, TU Dresden. A four point loading method is used on the machine for testing the flexural strengths of the specimens. The testing is performed according to test standards DIN EN ISO 527-4 for tensile and DIN EN ISO 14125 for flexural strength. The impact tests are

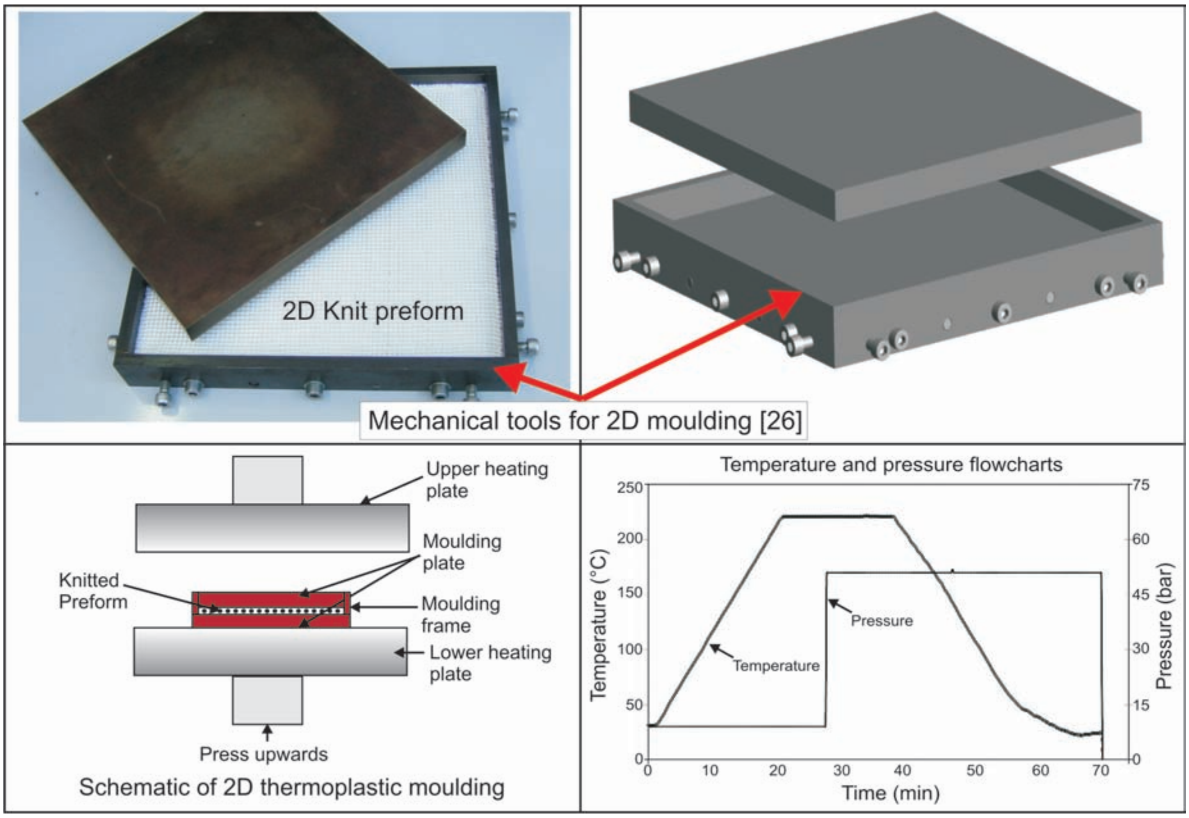


Figure 6.4: Thermoplastic consolidation of 2D knit preforms

carried out with the aid of a pendulum arm type impact tester, which functions based on the principle of Charpy Impact Test technique. Testing is carried out at the Institute of Lightweight Engineering and Plastic Technology (ILK) of TU Dresden. Standard methods of sampling and testing are applied as stated in DIN EN ISO 179-2. However, the volume of glass filaments in all composites is measured by buring test and it is already documented in Table 6.1.

6.2.2 Tensile properties of 2D knit composites

The tensile properties of composites produced from different knit fabrics have been presented in Figure 6.5 (a, b, c, d). The tensile properties in both directions improve from composites with knit loops (K) to tuck stitches

(T), whereas these properties are maximum only in course direction for weft yarns (W). But, these tensile properties are recorded very improved in both wales and course directions (in 0° & 90°) for knit fabric with reinforcement yarns integrated as weft and warp inlays (WWA). However, tensile properties are found very improved in level especially in wales direction for knit fabrics type WA, WAT and WWAT in which the reinforcement yarns are integrated as warp inlays with different course directional reinforcements. The variation of tensile properties in wales direction among the above mentioned fabric types could be well explained by the dissimilar values of wales per centimetre caused to different levels of course directional forces to be carried by respective knit structures. However, among

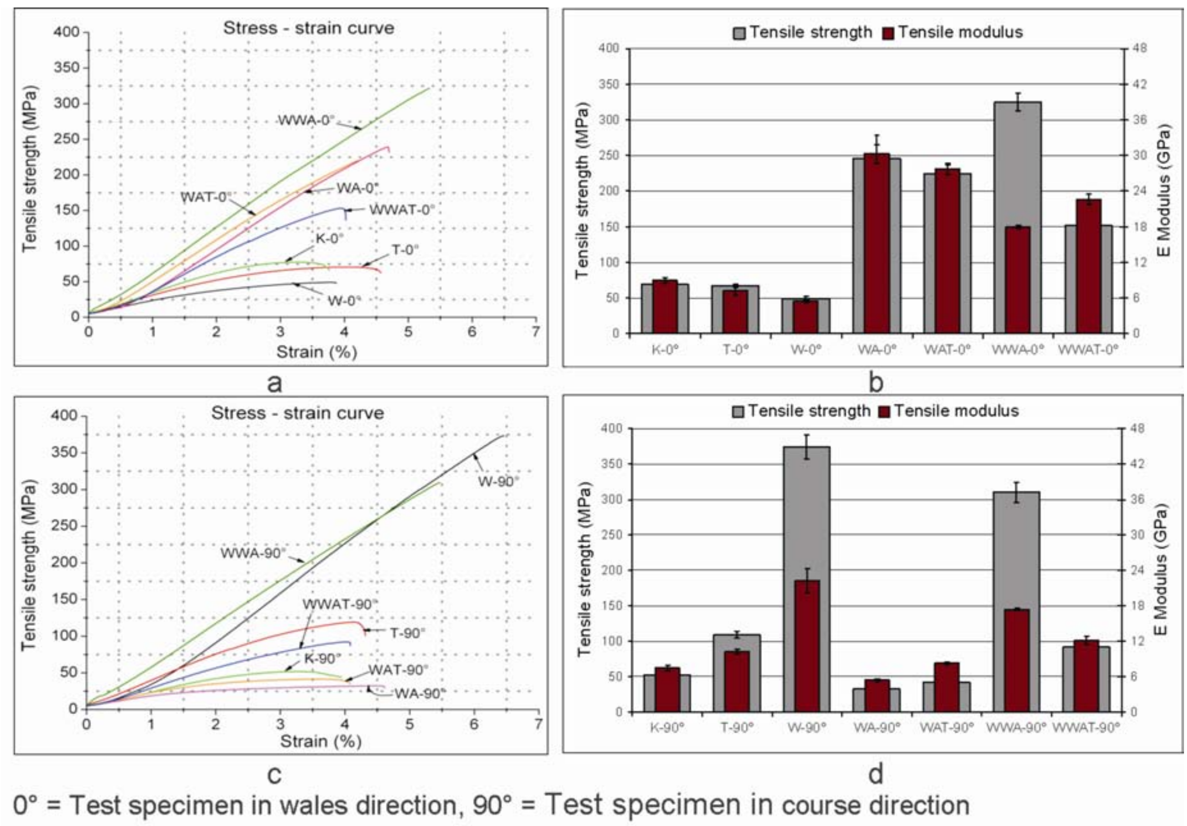


Figure 6.5: Influence of yarn arrangments on the tensile properties of 2D knit composites

them only the knit structure WWAT shows few improvements in tensile testing especially in course direction because of the presence of weft inlays along with tuck stitch shaped course directional reinforcement yarns. On the other hand, this effect is not found enhanced than that of tuck stitches (T) due to the lower number of courses per centimetre (Table 6.1). Along with the reduction in glass filament breakage when knitted, the fully orientation of reinforcement yarns as weft and warp inlays (non-crimp yarns) are the cause for such superior tensile properties in wales and course directions of composites with reinforcement yarns as weft and warp inlays (WWA). For composites with tuck stitches (T) and knit loops (K), the effect of inferior tensile properties can be assumed as the product of the so-called curvilinear shapes of reinforcement yarns which seem to cause damage to the reinforcing glass filaments and a lack of proper fiber orientation.

6.2.3 Flexural properties of 2D knit composites

Keeping in view the analysis of flexural properties from Figure 6.6 (a, b, c, d), the overall comparison of the knit structures can be ranked as most advantageous only in the wales direction for composites with reinforcement warp yarns (WA), with warp yarns along with tick stitches (WAT), as most advantageous only in the course direction for composites with reinforcement weft yarns (W) and in both directions for composites with reinforcement warp and weft yarns (WWA) respectively. Knit structures can also be ordered as modestly advantageous in the both direction for composites with tuck stitches (T) and with biaxial inlays along with tuck stitches (WWAT). On the other hand, very inferior flexural properties are recorded in both directions for composites with reinforcement yarns as knit loops (K), in wales direction for weft yarns (W), in course direction for composites with warp yarns (WA) and for warp yarns together with tuck stitches (WAT). These effects are endorsed by the already men-

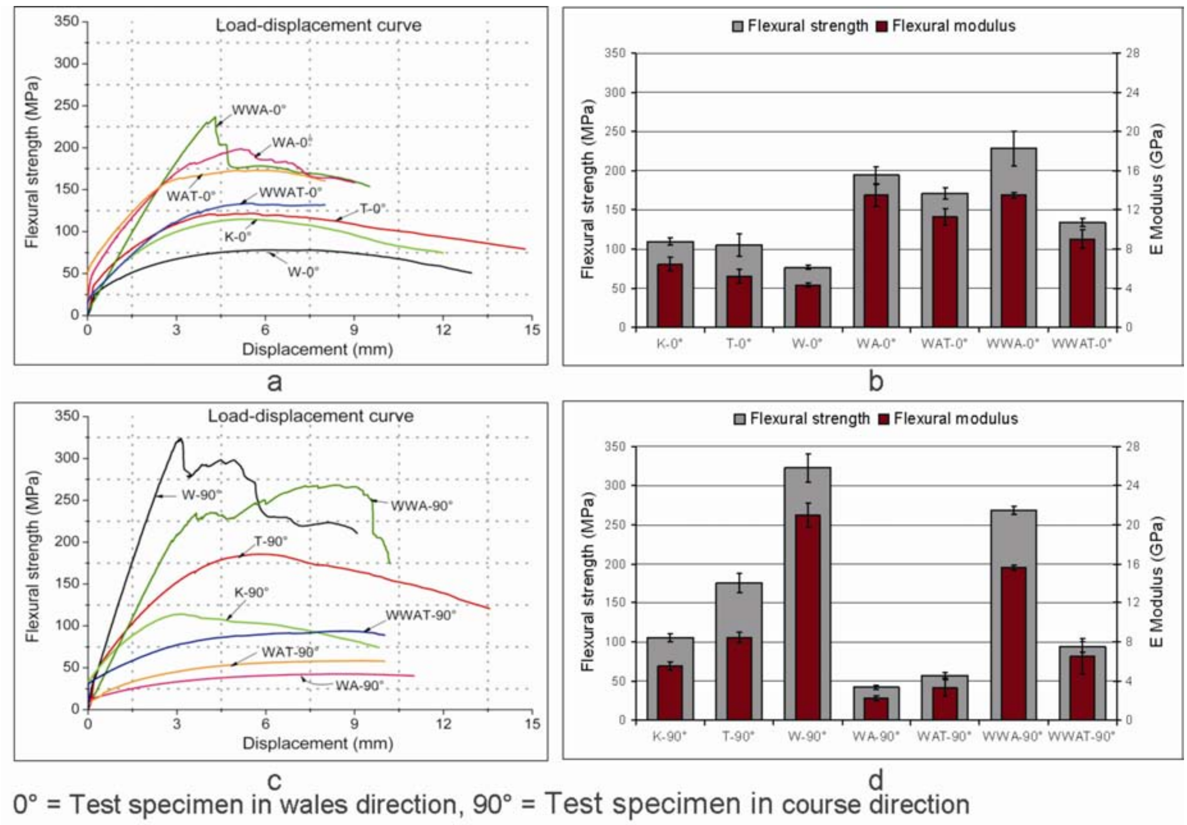


Figure 6.6: Influence of yarn arrangments on the flexural properties of 2D knit composites

tioned combined effect of orientation and damage of reinforcement glass filaments.

6.2.4 Impact properties of 2D knit composites

The results pertaining to the impact testing do not exhibit the same trends as they are recorded in case of tensile and flexural testing. The Figure 6.7 (a, b, c, d) elaborates the measured trends. The maximum impact strength and energy absorption are recorded for weft yarns (W) and warp yarns (WA) in fiber orientated course and wales directions respectively as usual, whereas tuck stitches (T) in course direction report better impact properties nearly equal to the weft yarns. For the composites with biaxial inlays (WWA) these properties are not as significant as they are in tensile and flexural testing. Conversely, integration of reinforcement yarns as knit loops (K) show also good resistance against impact in both wales and course directions and these results are nearby equal to the results of biaxial inlays (WWA). But, knit structures WAT and WWAT reveal the same tendency of results as they are in tensile and flexural testing. From the above results a view point could be forwarded, with the impact of impactor, the specimens experience slow displacements and contact forces reach their maximum levels due to good toughness in course direction of composites with reinforcement yarns as weft yarns (W), tucks stitches (T) and in wales direction of warp yarns (WA) respectively. Generally,

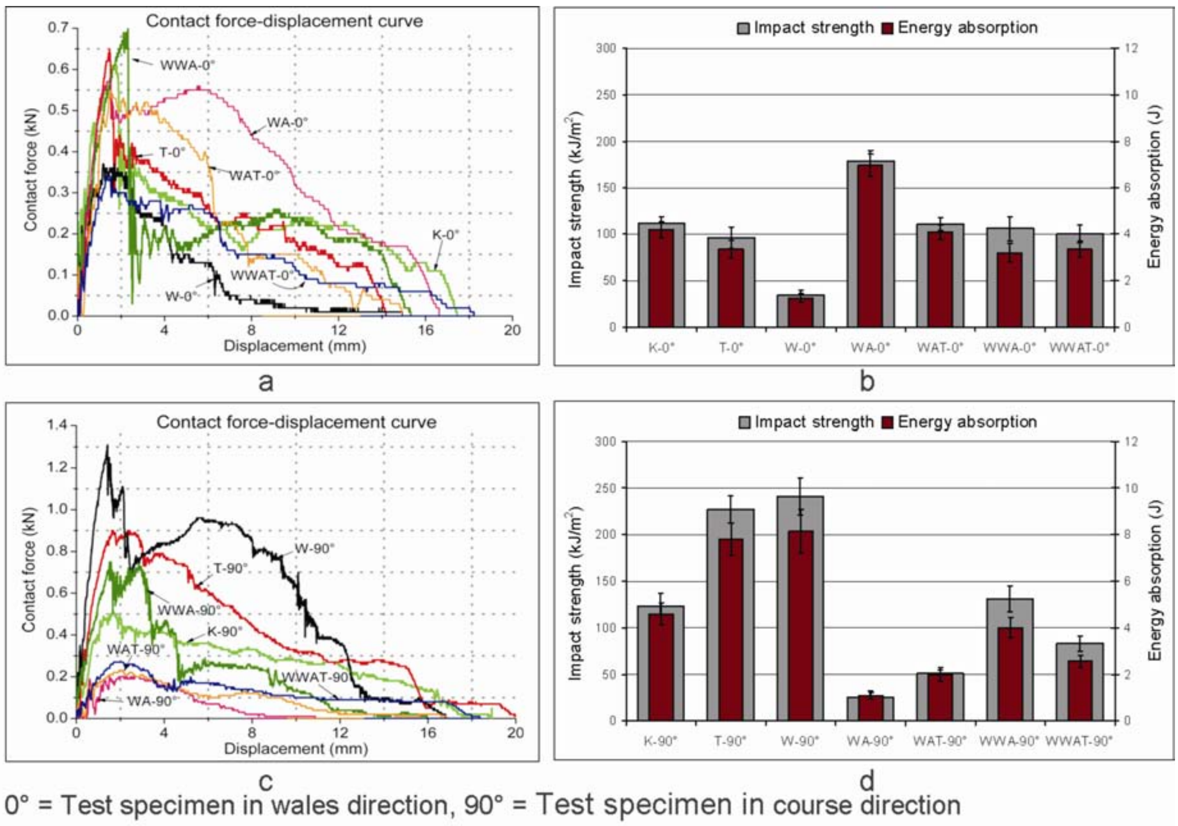


Figure 6.7: Influence of yarn arrangments on the impact properties of 2D knit composites

composites absorb energy during fracture mechanisms like delamination, shear cracking and filaments breakage. The presence of reinforcement filaments resists the deformation of the specimens leading to improved impact strength and energy absorption in filaments direction. Moreover, it is assumed that along with the damages of the reinforcement glass filaments by knitting the orientation of reinforcement filaments contribute to the performance of a knit structure against impact. Consequently, improved impact properties are recorded in case of the fabric structures with the integration of reinforcement yarns as curvilinear knit loops (K) and tuck stitches (T), whereas the higher courses per centimetre and higher wales per centimetre along with fully orientation of filaments cause the superior impact properties in course and wales directions for the knit structures with weft yarns (W) and warp yarns (WA) respectively.

Considering the analysis of the mechanical properties of 2D composites illustrated in Figures 6.5 to 6.7 and in Table 6.2, the integration of reinforcement yarns as multi-layered biaxial inlays (WWA) into knit fabric could be ranked as the most effective method, especially for very improved tensile and flexural properties as well as moderately improved impact properties in both wales and course directions. In addition, impact properties could be improved by introducing the tuck stitch shaped knit fabric (T) together with the biaxial reinforced knit fabric (WWA) as multiple layers in consolidation process. However, knit fabrics with the reinforcement yarns integrated as only weft yarns (W) and only warp yarns (WA) are in fact the uni-directional reinforced knit structures and offer superior mechanical properties only in the respective reinforcement directions (in course direction for knit structure W and in wales direction for knit structure WA). These uni-directional reinforced knit fabrics could replace the conventional yarn-winding technique for the manufacturing of uni-directional reinforced composites. Furthermore, these uni-directional reinforced knit fabrics could be assembled in different directions as multiple layers in consolidation process to produce multi-directional reinforced 2D composites. On the other hand, the integration of reinforcement yarns

Type	Test specimen in	Tensile properties		Flexural properties		Impact properties	
		Strength (MPa)	E Modulus (GPa)	Strength (MPa)	E Modulus (GPa)	Strength (KJ/m^2)	Energy absorption (J)
K	0°	69	9	110	6.5	112	4.2
K	90°	52	7.4	106	5.5	124	4.6
T	0°	68	7.1	105	5.2	96	3.4
T	90°	109	10.2	175	8.5	227	7.8
W	0°	49	5.5	77	4.4	35	1.3
W	90°	374	22.1	323	21	241	8.1
WA	0°	246	30	194	13.5	179	7
WA	90°	32	5.3	42	2.3	26	1.1
WAT	0°	224	27.8	171	11.3	111	4.1
WAT	90°	42	8.3	57	3.3	51	2
WWA	0°	325	18	228	13.5	106	3.2
WWA	90°	310	17.3	268	15.6	131	4
WWAT	0°	152	22.6	134	9	100	3.4
WWAT	90°	92	12.1	94	6.5	83	2.6

Table 6.2: Mechanical properties of 2D knit composites

as tuck stitches may be the substitute method for the medium level of mechanical properties if the multi-layered biaxial reinforcements are not possible. Again, the knit structures WAT and WWAT are significant only in the wales direction.

According to the above analysis of mechanical properties of 2D knit composites, the 3D thermoplastic composites consolidated from multi-layer reinforced (as weft and warp inlays) complex shaped innovative 3D spacer fabrics are predicted to show superior mechanical performances in lightweight applications.

Chapter 7

Mathematical analysis of tensile properties

Unlike the conventionally used isotropic materials, textile reinforced composites can be specifically customised in terms of their material properties for particular loading situations by modifying the fiber architecture, fiber orientation and material combinations. In this research, the flat knitting technology is developed further to manufacture innovative complex shaped multi-layer reinforced 3D spacer fabrics for high performance composite applications. Conversely, these 3D spacer fabrics are manufactured using commingled GF-PP hybrid yarns for thermoplastic consolidation. Moreover, in order to tailor the mechanical performances, the reinforcement yarns can be arranged differently in the fabric structures using the innovative knitting techniques. The analysis of the mechanical properties of 2D knit fabrics with different arrangements of reinforcement yarns presented in Chapter 6 shows that the mechanical performances of textile reinforced thermoplastic composites are customized greatly by the type of component materials as well as the arrangement of fibers into the structures. Besides, it is assumed that the integrated manufacturing processes from hybrid yarn manufacturing to thermoplastic consolidation of textile preforms play also a significant role on the state of mechanical properties of component materials comparing to the properties of composites. Therefore, it is indispensable to investigate the effect of manufacturing processes on the mechanical properties of composites, especially comparing to the theoretical (calculated mathematically) and experimental properties. If such investigation could be done on the 2D knit fabrics (individual fabric layers) of knitted multi-layer reinforced 3D spacer fabrics, it would be effortless to predict the mechanical performances of 3D composites made from 3D spacer fabrics. However, in this present research work, the simple mathematical calculations are carried out to predict the tensile properties of GF-PP hybrid yarns, multi-layer reinforced 2D knitted fabrics and 2D knit composites. These prediction systems along with the comparison of predicted and experimented results are presented into following subsections.

7.1 Calculation and comparison of tensile strengths of commingled hybrid yarns

Hybrid yarns consisting of reinforcing and thermoplastic matrix materials as filaments are suitable for consolidation process in order to reduce the problems associated with high melt viscosity of thermoplastic matrix. Among all methods of hybrid yarn manufacturing, commingling process is considered to be the most flexible method allowing soft and drapeable yarn with high level of distribution homogeneity of the component materials. Consequently, this commingling process is preferred for the development and manufacturing of GF-PP hybrid yarns (both finer loop yarn and coarser reinforcement yarns) in the frame work of the research project SFB 639 [26] at ITM, TU Dresden. These yarns are used to develop the complex shaped textile preforms for lightweight applications. In commingled GF-PP hybrid yarn manufacturing process, the glass filaments (GF) as reinforcing material and polypropylene filaments (PP) as matrix material are scattered among one another at the filament level (intimate mixing) in a nozzle by means of compressed air. But, the glass filaments, which have very poor bending properties and show extremely brittleness as end effect, are subjected to be damaged considerably by the commingling process, especially with the perpendicular or nearly perpendicular flow of compressed air to the filament direction. Since these glass filaments are the only one reinforcing component of GF-PP hybrid yarn and such hybrid yarn is used to reinforce the textile preforms for high performance composite applications, it is noteworthy to estimate as well as to compare the amount of ultimate tensile strength of GF-PP hybrid yarn considering the tensile strengths of their component materials. Such comparison of the predicted and the experimented tensile properties of commingled GF-PP hybrid yarns would allow finding out the level of degradation of tensile properties of yarns by the commingling process. The tensile properties could be calculated theoretically based on the equation for the specific hybrid yarn fineness consisting of different component materials by commingling process. The equation for manufacturing of specific hybrid yarn fineness from different component materials is given below:

$$F_h = n_r \cdot F_r \cdot f_r + n_m \cdot F_m \cdot f_m \qquad (7.1)$$

Where, F_h is the fineness (in tex) of manufactured hybrid yarn, n_r is the number of reinforcing filament-roving, F_r is the fineness (in tex) of reinforcement filament-roving, f_r is the level of feeding of reinforcement filament, n_m is the number of matrix filament-roving, F_m is the fineness (in tex) of matrix filament-roving, f_m is the level of feeding of matrix filament. Consequently, the percentage of mass as well as volume of component materials in the manufactured hybrid yarn could be calculated theoretically (on the basis of equation 7.1) by the following formulas:

$$G_r\% = \frac{n_r \cdot F_r \cdot f_r}{(n_r \cdot F_r \cdot f_r + n_m \cdot F_m \cdot f_m)} \times 100 \tag{7.2}$$

$$G_m\% = \frac{n_m \cdot F_m \cdot f_m}{(n_r \cdot F_r \cdot f_r + n_m \cdot F_m \cdot f_m)} \times 100 \tag{7.3}$$

$$V_r\% = \frac{G_r}{\rho_r} \times 100 \tag{7.4}$$

$$V_m\% = \frac{G_m}{\rho_m} \times 100 \tag{7.5}$$

Where, G_r and G_m are the mass of the reinforcing and matrix components respectively, V_r and V_m are the volume of the reinforcing and matrix components accordingly, ρ_r and ρ_m are the density (in g/cm^3) of the reinforcing and matrix components in that order. Also, the tensile strength of manufactured commingled hybrid yarn could be calculated theoretically using the following formula:

$$T_{ht} = (n_r \cdot f_r \cdot T_r + n_m \cdot f_m \cdot T_m) \cdot (1 - \Delta_h) \tag{7.6}$$

Where, T_{ht} is the tensile strength of manufactured hybrid yarn calculated theoretically, T_r is the tensile strength of the reinforcement filament-roving, T_m is the tensile strength of the matrix filament-roving, Δ_h is the loss of tensile strength (in %) of component materials by commingling hybrid yarn manufacturing process. The degradation of tensile strength of component materials by commingling process could be calculated using the calculated tensile strength (assuming $\Delta_h = 0$ in equation 7.6) as well as the experimented tensile strength (T_{he}) of hybrid yarns in the following formula:

$$\Delta_h\% = \frac{(T_{ht} - T_{he})}{T_{ht}} \times 100 \tag{7.7}$$

Conversely, in order to investigate the effect of commingling process on the tensile strengths of hybrid yarns, the GF-PP hybrid yarns of three different finenesses, which are developed in the frame work of SFB 639 [26] at ITM, TU Dresden, are considered. The details of component materials and parameters for the manufacturing of these GF-PP hybrid yarns by commingling process are documented in Table 7.1.

Hybrid yarn fineness	**Reinforcement material (E-Glass): GF**		**Matrix material: PP**		**Parameters of commingling process**				**Volume of components in hybrid yarn**	
F_h **(tex)**	F_r **(tex)**	T_r **(N)**	F_m **(tex)**	T_m **(N)**	n_r	f_r (%)	n_m	f_m (%)	GF (%)	PP (%)
138	68	39	32	9.4	1	101.9	2	104.9	52	48
410	300	103	32	9.4	1	101.9	3	104.6	52	48
1110	410	150	32	9.4	2	102	8	103.5	52	48

Table 7.1: Details of component materials and parameters of commingling process for manufacturing of GF-PP hybrid yarns [26]

The manufactured hybrid yarns are used to investigate the tensile properties on the Zwick Z100 testing machine (Zwick GmbH & Co. KG, Germany) at ITM, TU Dresden and the measured results are compared with their respective tensile strengths calculated theoretically (using the equation 7.6). The theoretical calculation of tensile strength is followed assuming that the commingling process has no influence on the state of tensile strengths of component materials (assuming $\Delta_h = 0$ in equation 7.6). The intention is to find out the actual degradation of tensile strength comparing to the theoretical (ideal) and experimental results. Moreover, two predictions of actual tensile strength are calculated taking into consideration of possible minimum and maximum level of degradation of tensile strength by commingling process about 60% and 70% respectively. The Figure 7.1 presents all theoretical and experimental tensile strengths of GF-PP hybrid yarns.

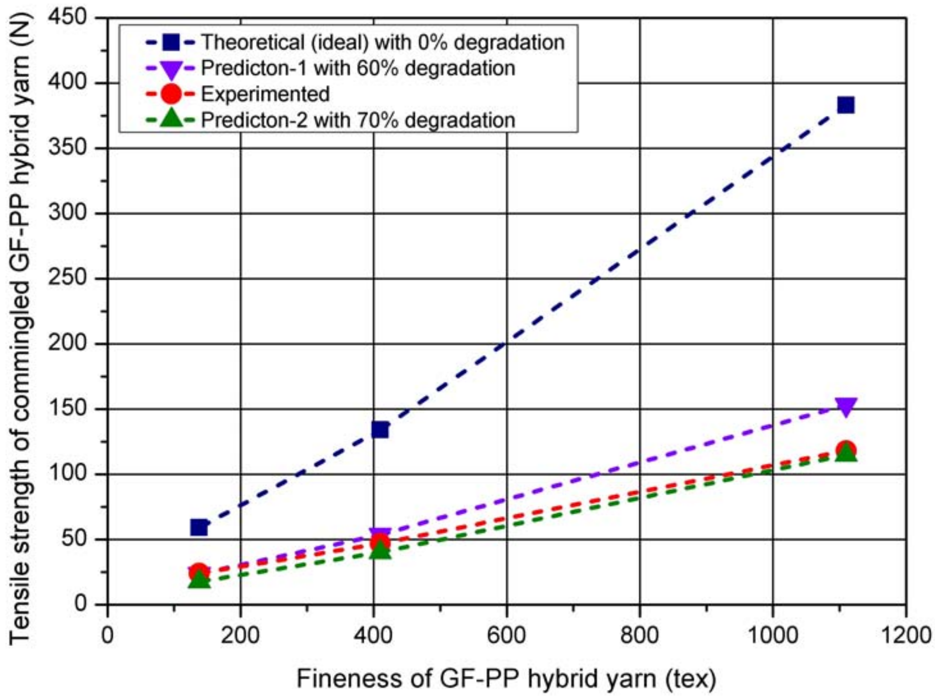


Figure 7.1: Tensile strength of commingled GF-PP hybrid yarn

The comparison of theoretical (ideal) and experimental tensile strengths shows a clear trend that the component materials, especially the reinforcing component glass filaments are damaged to a great extent by the commingling process while manufacturing the GF-PP hybrid yarns. The level of actual degradation of tensile strengths (by equation 7.7) of GF-PP hybrid yarns in a volume combination of 52% and 48% respectively is found about 65% (mean value). The cause of such degradation of tensile strength is the already mentioned fact that, the very brittle glass filaments are damaged mostly in the nozzle due to the force of compressed air, where the filaments are opened individually from the roving-strand and mixed homogenously with the matrix filaments. Despite that, the tensile properties are considered to be improved especially in the formation of composites because of the enhanced matrix-filament interfacial bonding developed by the thermoplastic consolidation process. Moreover, the epic features of commingling process for hybrid yarn manufacturing, for instance, suitability in homogeneous mixing of the components, versatility of manufacturing process, cost-effectiveness, compatibility for both textile preforming as well as thermoplastic consolidation processes, realizing of soft, flexible and drapeable yarns have made this technology extremely promising for the hybrid yarn manufacturing, especially for thermoplastic composite industries.

7.2 Calculation and comparison of tensile strength of multi-layer reinforced 2D knitted fabric

The mechanical performance, especially the strength of knitted fabric is a concern in composite application due to the looped, curved architecture of the fibers. The complex nature of the knitted structures generally does not exhibit distinct directions where the strength is at maximum, but the knit preform properties are greatly influenced by the fiber strength, modulus, type of yarn, knitted structure, stitch density, number of knit fabrics ply, pre-stretch parameters, inlays and other knitting parameters. Consequently, the mechanical performances of a composite material reinforced by a knitted fabric mostly dependent on the fabric properties. For this reason, knowledge on the tensile properties of the knitted fabrics is required in order to predict the corresponding properties of the composites. Various authors have investigated the tensile properties of plain weft knits [116–123] and most of these investigations are based on the micromechanics of knitted fabrics. The unit cell, often a single loop, is used for these complex analyses, and the tensile properties of knitted fabrics are directly derived from the loop configuration and yarn properties. Conversely, the simplified model proposed by Aart *et al.* [124] reports the calculation of tensile strength of knitted fabric on the basis of stitch geometry. They estimated the tensile strength of interlock knitted fabric with weft inlays by dividing the interlock structure into two single jersey knit structures as well as modeling the curved loops as straight fiber sections.

According to the discussion (Chapter 6) on mechanical properties of 2D composites reinforced by different knitted structures, it is documented that the multi-layer reinforced knitted fabric (knitted structure WWA of Figure 6.2) is the most effective knitted structure for improved mechanical properties in both wales and course directions. Therefore, it is preferred to model as well as to investigate the tensile properties of this multi-layered knitted structure. Since the selected multi-layer reinforced knitted fabric is consisted of single jersey knit structure (using only finer loop yarns) and reinforcement inlay yarns (coarser yarns for structural reinforcement), the tensile strength of such multi-layered knitted preform could be calculated theoretically by further modifying the above mentioned simplified model [124]. In order to calculate the tensile strength, the multi-layered knitted fabric is first divided into their base fabric structures, which are the single jersey knit structure (sub-structure-1 of Figure 7.2) knitted using finer loop yarn and the multi-layered arrangements of reinforcement yarns (sub-structure-2 of Figure 7.2). The ultimate tensile strength of this multi-layer reinforced knitted fabric is the combined tensile effect of both sub-structures derived from the main fabric structure. Therefore, the further calculation of tensile strength is done separately on both sub-structures.

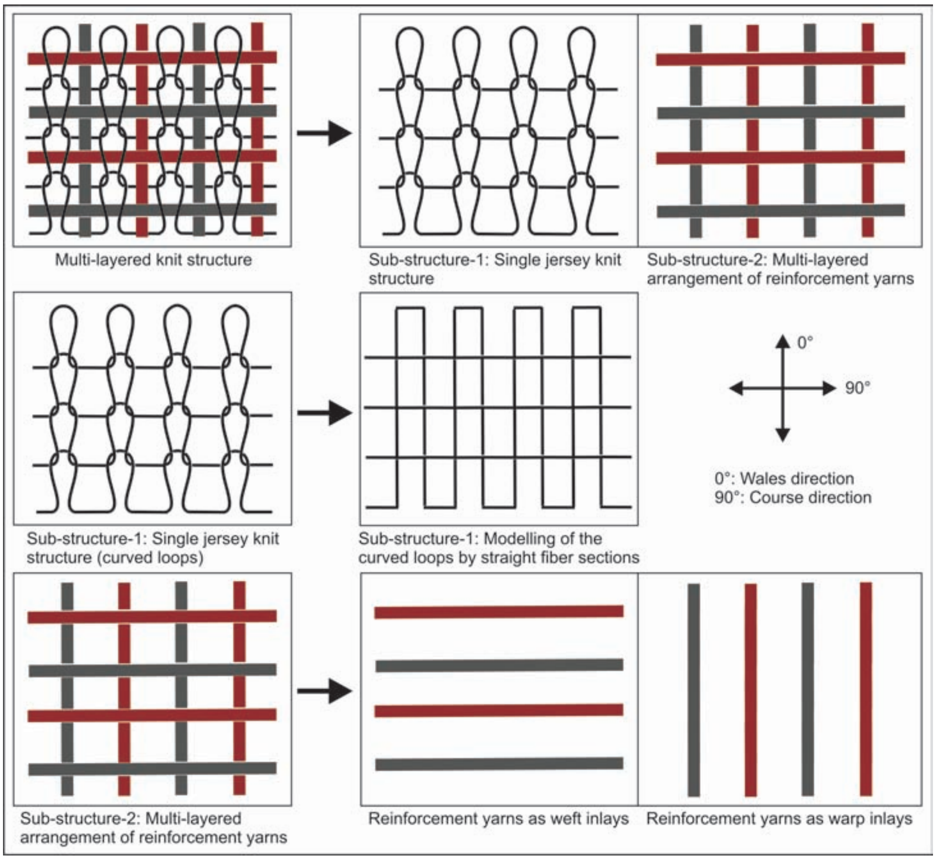


Figure 7.2: Sketch of multi-layered knitted fabric, sub-structures and simple model geometry with straight fiber segments

By assuming the curved loops of single jersey knitted structure as straight fiber sections as shown in the Figure 7.2 (modeling of sub-structure-1 by straight fiber sections), the following equations could be formulated:

$$T_{yl0^\circ} = T_{hel} \cdot n_{yl0^\circ} \cdot W \cdot (1 - \Delta_{kl}) \tag{7.8}$$

$$T_{yl90^\circ} = T_{hel} \cdot n_{yl90^\circ} \cdot C \cdot (1 - \Delta_{kl}) \tag{7.9}$$

$$L_{yl} = W \cdot C \cdot L_l \cdot 100 \tag{7.10}$$

$$G_{yl} = \frac{L_{yl} \cdot t_l}{1000} \tag{7.11}$$

Where, T_{yl0° and T_{yl90° are the tensile strengths in wales (in 0°) and course (in 90°) directions of curved loop structure (sub-structure-1) per 1 cm^2 respectively, T_{hel} is the measured tensile strength of finer loop yarn (before knitting), n_{yl0° and n_{yl90° are the number of straight fiber sections in the wales and course directions correspondingly for unit knit-loop structure (normaly 2 in the wales direction and 1 in the course direction), W and C is the number of wales/cm and courses/cm in that order, Δ_{kl} is the degradation of tensile strength of finer yarn curved as knit loops by knitting process, L_{yl} is the total length of finer loop yarns (m/m^2), L_l is the length of single loop (in cm), G_{yl} is the fabric weight (g/m^2), t_l is the yarn fineness (tex) of finer loop yarn (yarn weight in g/km). On the other hand, the tensile strength of reinforcement inlay yarns arranged as multi-layered in the sub-structure-2 of Figure 7.2 could be calculated using the fabric specifications (for example, wales/cm and courses/cm) as well as the measured tensile strength of reinforcement yarn before knitting. Consequently, the following equations could be derived based on the sub-structure-2 of Figure 7.2:

$$T_{yr0^\circ} = T_{her} \cdot W \cdot (1 - \Delta_{kr0^\circ}) \tag{7.12}$$

$$T_{yr90^\circ} = T_{her} \cdot C \cdot (1 - \Delta_{kr90^\circ}) \tag{7.13}$$

$$L_{yr0^\circ} = W \cdot 100 \tag{7.14}$$

$$L_{yr90^\circ} = C \cdot 100 \tag{7.15}$$

$$G_{yr0^\circ} = \frac{L_{yr0^\circ} \cdot t_{r0^\circ}}{1000} \tag{7.16}$$

$$G_{yr90^\circ} = \frac{L_{yr90^\circ} \cdot t_{r90^\circ}}{1000} \tag{7.17}$$

$$G_{yr} = G_{yr0^\circ} + G_{yr90^\circ} \tag{7.18}$$

Where, T_{yr0° and T_{yr90° are the tensile strengths in wales (in 0°) and course (in 90°) directions of multi-layer reinforced structure per 1 cm^2 respectively (sub-structure-2 of Figure 7.2), T_{her} is the measured tensile strength of reinforcement yarn (before knitting), Δ_{kr0° and Δ_{kr90° are the degradation of tensile strengths of reinforcement yarns due to their integration as warp and weft inlays by knitting process correspondingly, L_{yr0° and L_{yr90° are the total lengths (m/m^2) of reinforcement warp and weft inlays in that order, G_{yr0° and G_{yr90° are the weight of warp and weft inlays respectively (g/m^2), G_{yr} is the total weight of multi-layer reinforced structure (g/m^2), t_{r0° and t_{r90° are the yarn fineness (in tex) of reinforcement warp and weft inlays correspondingly. Also, the ultimate tensile strength and the specific weight of multi-layer reinforced knitted fabric (combined structure of sub-structure-1 and sub-structure-2 in Figure 7.2) could be calculated theoretically using the following equations:

$$T_{f0^\circ} = T_{yl0^\circ} + T_{yr0^\circ} \tag{7.19}$$

$$T_{f0^\circ} = W \cdot w_{90^\circ} \cdot \{ T_{hel} \cdot n_{yl0^\circ} \cdot (1 - \Delta_{kl}) + T_{her} \cdot (1 - \Delta_{kr0^\circ})\} \tag{7.20}$$

$$T_{f90^\circ} = T_{yl90^\circ} + T_{yr90^\circ} \tag{7.21}$$

$$T_{f90^\circ} = W \cdot w_{0^\circ} \cdot \{ T_{hel} \cdot n_{yl90^\circ} \cdot (1-\Delta_{kl}) + T_{her} \cdot (1-\Delta_{kr90^\circ})\} \tag{7.22}$$

$$G_f = G_{yl} + G_{yr} \tag{7.23}$$

$$G_f = \frac{(W \cdot C \cdot L_l \cdot t_l + W \cdot t_{r0^\circ} + C \cdot t_{r90^\circ})}{10} \tag{7.24}$$

Where, T_{f0° and T_{f90° are the tensile strengths in wales (in 0°) and course (in 90°) directions of multi-layer reinforced knitted structure for fabric width w (in cm) respectively, G_f is the total weight of multi-layer reinforced knitted structure (g/m^2). Conversely, in order to compare the predicted and experimented tensile strengths and fabric specific weights of multi-layered knitted structure, three different multi-layered knitted structures (with variable yarn finesses), which are developed and knitted using GF-PP hybrid yarns in the frame work of SFB 639 [26] at ITM, TU Dresden, are considered. The details of yarns used for multi-layered knitted fabrics and the fabric specifications of such fabrics are given in Table 7.2 and 7.3 respectively. It is already known that tensile strengths of commingled GF-PP hybrid yarns (in a volume combination of 52% and 48%) are degraded about 70%, 10% and 5% by knitting process for being integrated in the knitted structure as knit loops, warp yarns and as weft yarns respectively (according to the section 6.1.2). Also, these levels of degradation are also considered while calculating the tensile strength of fabric theoretically. However, in order to obtain the experimented tensile strength, the selected multi-layered knitted fabrics are used to measure

	Fineness of (GF-PP) hybrid yarn			
Details of yarn	**138 tex**	**410 tex**	**1230 tex**	**1640 tex**
Volume of GF & PP in yarn structure	52 % & 48 %	52 % & 48 %	52 % & 48 %	52 % & 48 %
Measured yarn tensile strength before knitting	24 N	47 N	120 N	165 N
Yarn integrated in knitted structure as:	Knit loop	Weft yarn	Weft & warp yarns	Weft & warp yarns
Degradation of yarn tensile strength by knitting process	70 % (Δ_{kl})	5 % (Δ_{kr90°)	10 % (Δ_{kr0°), 5 % (Δ_{kr90°)	10 % (Δ_{kr0°), 5 % (Δ_{kr90°)

Table 7.2: Details of yarns used for multi-layered knitted fabrics

	Fabric identification		
Fabric specification	**V2a**	**V2d**	**V4**
Fineness of loop yarn (tex)	138	138	138
Fineness of weft yarn (tex)	1230	1640	410
Fineness of warp yarn (tex)	1230	1640	1230
Wales/cm	2.78	2.77	2.87
Courses/cm	2.72	2.85	2.75
Loop length(cm)	1.32	1.37	1.29

Table 7.3: Fabric specifications of different multi-layered knitted fabrics

the tensile properties on the Zwick Z100 testing machine (Zwick GmbH & Co. KG, Germany) at ITM, TU Dresden following the test standard DIN EN ISO 13934-1. The Figure 7.3 (a & b) represents the comparison of theoretical (ideal) and experimental tensile strengths of multi-layered knitted fabrics, where the Figure 7.4 illustrates fabric specific weights. In case of tensile strengths in both course and wales directions, the mean absolute error are calculated the same which is about 9%. On the other hand, the mean absolute error for fabric specific weights is found less than 3%. The results clearly show a highly significant resemblance between the experimental and predicted values. Consequently, the proposed model could be efficiently used in order to predict the tensile strength, amount of straight fibers in each direction (loop and inlay yarns) as well as the fabric specific weight of multi-layer reinforced knitted fabric manufactured by hybrid yarns.

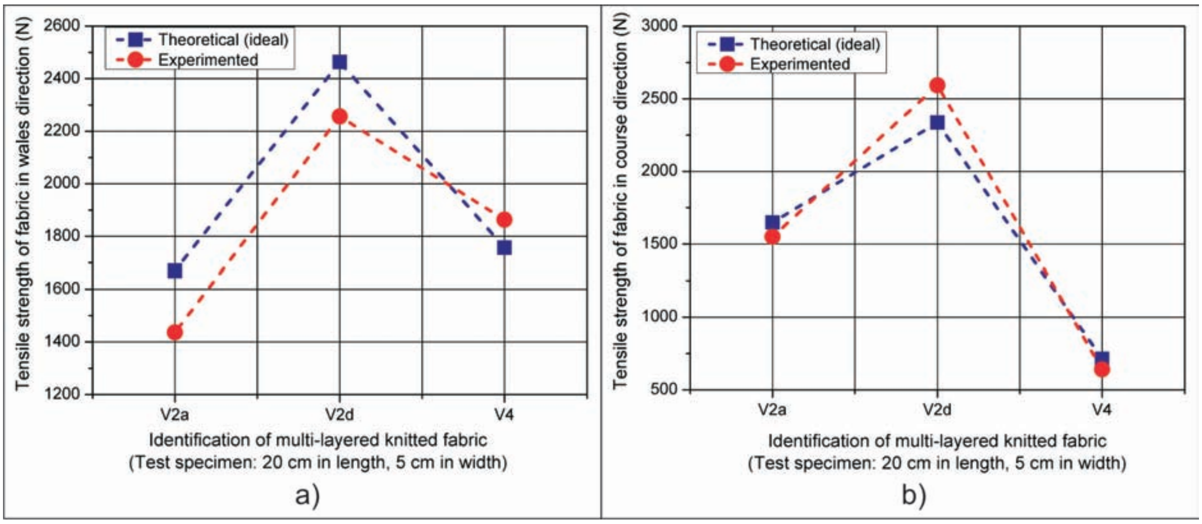


Figure 7.3: Tensile strengths of multi-layered knitted fabrics

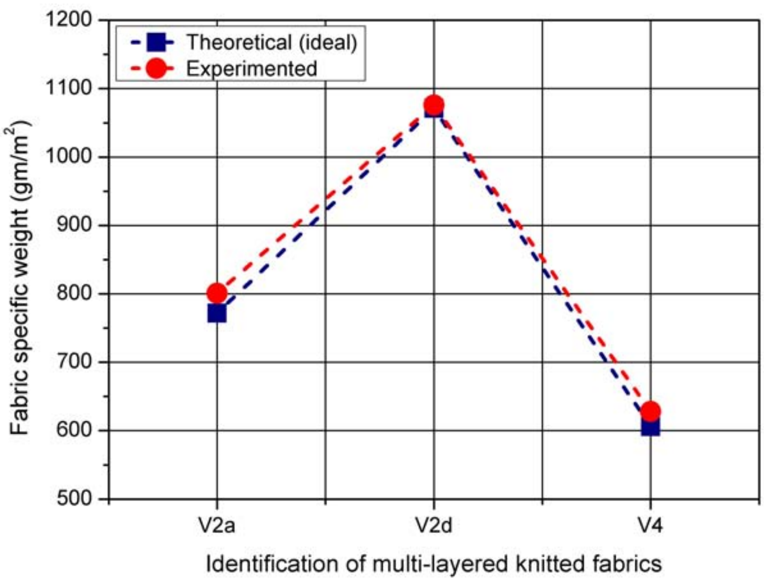


Figure 7.4: Specific weights of multi-layered knitted fabrics

7.3 Calculation and comparison of tensile properties of knit composites

Textile reinforced composites are produced through thermoplastic consolidation process from multi-layered knitted preforms manufactured using commingled GF-PP hybrid yarns. Since the reinforcement and matrix components are homogenously mixed at the yarn cross-section by commingling process and the knitted preforms are manufactured integrating the reinforcement inlays (non-crimp yarns) into the fabric structures, therefore, the simplest ways of measuring the tensile strengths and tensile modulus of such fiber reinforced composites are based on the rule of mixtures [124, 125]. The equations for measuring the tensile strength and tensile modulus based on rule of mixtures are given below:

$$T_c = \eta \cdot \sigma_r \cdot V_r + \sigma_m \cdot (1 - V_r) \tag{7.25}$$

$$E_c = \eta \cdot E_r \cdot V_r + E_m \cdot (1 - V_r) \tag{7.26}$$

Where, T_c and E_c are the tensile strength and tensile modulus of knit composite respectively, η is the efficiency factor of Krenchel (comparison of ply fibers in specific direction to the total ply fibers of both wales and course directions), σ_r and σ_m are the tensile strengths of reinforcement and matrix components accordingly, E_r and E_m are the tensile modulus of reinforcement and matrix components in that order. However, the equation 7.25 and 7.26 could be modified further for the multi-layered knitted fabrics with dissimilar finenesses as well as unlike numbers of inlay yarns in wales and course directions. The modified equations are:

$$T_{c0^\circ} = \{\Big(\frac{t_{r0^\circ}}{t_{r0^\circ} + t_{r90^\circ}}\Big) \cdot \Big(\frac{W}{C}\Big) \cdot \sigma_r \cdot V_r + \sigma_m \cdot (1 - V_r)\} \cdot (1 - \Delta_{ct0^\circ}) \quad (7.27)$$

$$E_{c0^\circ} = \{\Big(\frac{t_{r0^\circ}}{t_{r0^\circ} + t_{r90^\circ}}\Big) \cdot \Big(\frac{W}{C}\Big) \cdot E_r \cdot V_r + E_m \cdot (1 - V_r)\} \cdot (1 - \Delta_{ce0^\circ}) \quad (7.28)$$

$$T_{c90^\circ} = \{\Big(\frac{t_{r90^\circ}}{t_{r0^\circ} + t_{r90^\circ}}\Big) \cdot \Big(\frac{C}{C}\Big) \cdot \sigma_r \cdot V_r + \sigma_m \cdot (1 - V_r)\} \cdot (1 - \Delta_{ct90^\circ}) \quad (7.29)$$

$$E_{c90^\circ} = \{\Big(\frac{t_{r90^\circ}}{t_{r0^\circ} + t_{r90^\circ}}\Big) \cdot \Big(\frac{C}{C}\Big) \cdot E_r \cdot V_r + E_m \cdot (1 - V_r)\} \cdot (1 - \Delta_{ce90^\circ}) \quad (7.30)$$

Where, Δ_{ct} and Δ_{ce} are the degradation (in %) of tensile strength and tensile modulus of composite comparing to the properties of their component materials accordingly, 0° and 90° are in the wales and course directions respectively. Conversely, in order to compare the predicted and experimented results, the tensile properties of thermoplastic composites manufactured individually from three different multi-layered knitted fabrics (V2a, V2d and V4) are calculated first using the above formulated equations. In such calculation, the tensile strength and modulus of E-glass filaments are assumed to be 2800 MPa and 72.4 GPa respectively, whereas these properties are considered to be 30 MPa and 1.5 GPa for polypropylene accordingly (very common tensile properties of both E-glass and polypropylene) [52,112,113]. The volume of glass filaments of the composites made from fabric structures V2a, V2d and V4 are measured by burning test and it is found about 46.08%, 46.76% and 44.2% in that order. While calculating the theoretical (ideal) tensile properties, it is assumed that the component materials of composites do not loss any tensile properties by the intermediate processes from commingling to consolidation (assuming Δ_{ct} and Δ_{ce} are equal to zero). The intention is to find out the actual degradation of tensile properties comparing to the theoretical (ideal) and experimented results. Moreover, two predictions of actual tensile strength are calculated assuming the possible minimum and maximum level of degradation of tensile strength by intermediate processes (from yarn manufacturing to thermoplastic consolidation) about 50% and 60% respectively. Later on, these theoretical results are compared with the experimental values of the respective composites. The Figure 7.5 represents the predicted and experimented tensile properties of the different 2D knit composites.

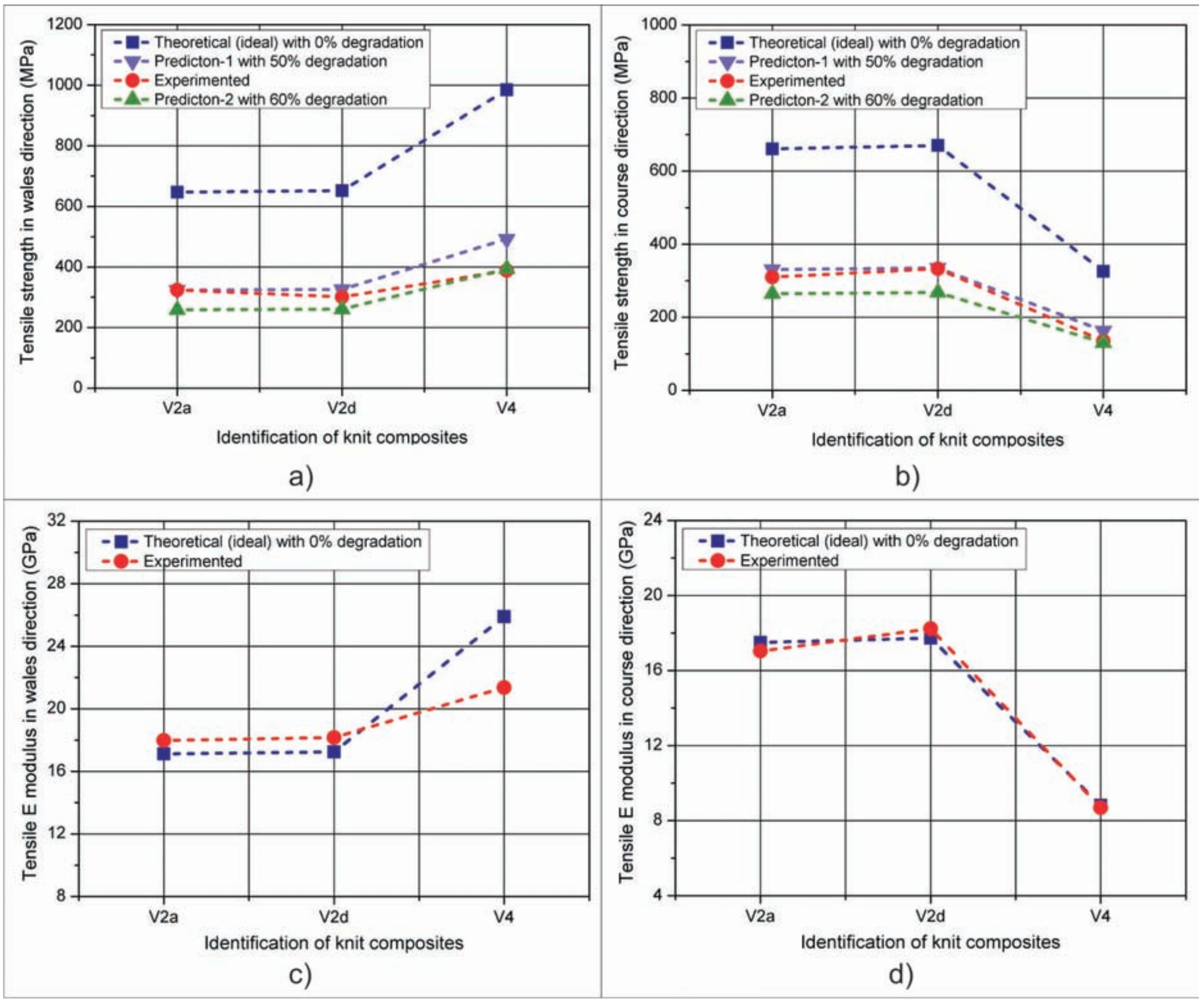


Figure 7.5: Tensile properties of 2D knit composites

Consistent with the comparison of tensile strengths presented in Figure 7.5 (a and b), the experimented tensile strengths in wales and course directions are found about 53% and 54% less than that of theoretical (ideal) results of different knit composites respectively. On the other hand, according to the Figure 7.5 (c and d), such degradation is recorded about 8% and 3% in that order in case of tensile modulus. It is already documented in section 7.1 that the tensile strength of GF-PP hybrid yarn is degraded about 65% by commingling process comparing to the tensile strengths of component materials. It is also claimed in section 6.1 that the GF-PP hybrid yarn loses again about 5-10% and 70% of remaining tensile strength for being integrated as inlay yarns (weft and warp yarns) and as knit loops by knitting process. If it is assumed that the total degradation of tensile strength of GF-PP hybrid yarn from commingling to the thermoplastic consolidation process is about 70%, however, an improvement has taken place in case of tensile strength, especially in the formation of composites. This improvement is reported about 25% of total tensile degradation caused by the intermediate processes (from hybrid yarn manufacturing to thermoplastic consolidation). It is believed that such improvements are the result of the filament-matrix interfacial bonding enhanced in composites, which resists the acted upon deformation forces as well as allows more force to be transferred. On the other hand, tensile modulus, which is the relationship between the strength and strain, is remained the same also in the formation of composite.

Comprehending all the above mentioned theoretical and experimental observations, it could be concluded that the tensile strength of commingled hybrid yarn can be calculated directly based on the tensile strengths of component materials as well as on their level of degradation by commingling process. The tensile strength of GF-PP hybrid yarn is found greatly influenced by the commingling process. The amount of such degradation of tensile strength of GF-PP hybrid yarn, which is manufactured in a volume combination of 52% (GF) and 48% (PP) respectively by commingling process, is found about 65%. Also, the proposed model reports a highly significant resemblance between the experimental and predicted values of tensile strengths and specific weights of multi-layered knitted fabrics. Therefore, such model could be applied to predict the tensile strength, portion of straight fiber in each direction as well as the specific weight of multi-layer reinforced knitted fabric. Besides, the tensile properties of thermoplastic composites consolidated from multi-layer reinforced knitted fabrics (made of commingled GF-PP hybrid yarns) can be predicted accurately on the basis of the rule of mixtures and using the tensile strengths of component materials along with the total amount of degradation of tensile strengths by the intermediate processes (commingling to consolidation). However, the thermoplastic consolidation process improves the tensile strengths considerably in the formation of composite (up to 25% of total tensile degradation caused by the intermediate processes) and this improvement is considered to be the result of the filament-matrix interfacial bonding enhanced in composites.

Chapter 8

Advantages and potential applications of flat knitted innovative 3D spacer fabrics

The developed solution for complex shaped innovative 3D spacer fabrics offers the chance for a significant extension of the structural diversity of the knitting technique. Consequently, it inaugurates the large scale applications in the field of lightweight construction and energy technology. This creates the possibility to improve and engineer the properties of knitted semi-finished products as well as to the development of entirely new solutions. Other possible applications include energy-absorbing structures in protective textiles and crash-relevant components in the automotive and mechanical engineering. The spacer fabrics also have a clear potential for the acoustic insulation. However, the advantages of 3D spacer fabrics by innovative flat knitting techniques are:

- Flexible manufacturing of complex shaped 3D spacer fabrics in a single process-step using high performance materials (yarns)
- 3D spacer fabrics with diverse geometries leading to various structural benefits (form follows force)

- Realization of complex geometries with double or multiple wall-structures in a single process-step
- Multi-layer reinforcements (non-crimp yarns up to 4 layers) for high mechanical performances (tensile strength, rigidity, energy absorption)
- Precise knitting of complex shaped preforms eliminating the additional processes
- No wastage due to "near to net" shaping using "Fully-fashion" technique
- Economical manufacturing due to low investment cost as well as single processing step
- Full-flexibilities in the usage of wide-spectrum of materials (from conventional to high performance)
- High potentiality to substitute the metal based panels by the spacer fabric based 3D composites in lightweight applications
- Suitable as crash-components (composites) for high energy absorption
- Structural health-monitoring through integrated "sensor-networks"
- Very good recyclability of thermoplastic textile composites
- Very effective to use in protective textiles
- Usage of space-chanals in various perspectives

The developed method offers a high potential for practical applications in lightweight industries. The Figure 8.1 shows some example for promising application fields of lightweight composite structures. It can be used

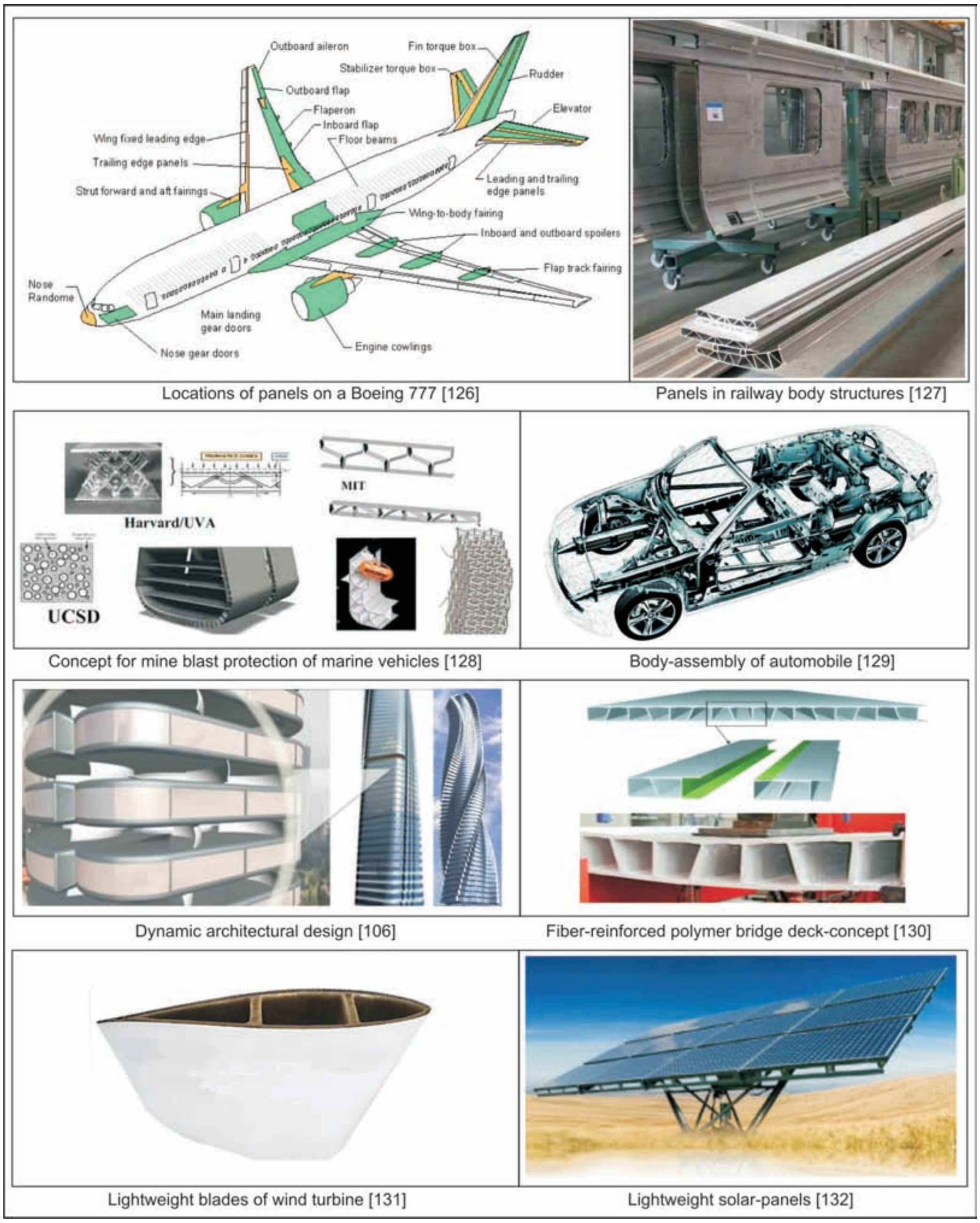


Figure 8.1: Potential application-fields (example) of lightweight structures based on flat knitted innovative 3D spacer fabrics [106, 126–132]

in vehicle manufacturing for the cost-rigid sandwich panel components (e.g. roof, door, deck, wing, under body construction) with short cycle times (approximately 1 minute in thermoplastic consolidation process). In addition, the empty-channels could be employed as fuel or hydrogen tank or their embodiment with sound damping material. The main advantage of the structure is the significant weight reduction. Consequently, they are very promising to substitute conventional metal based structures. Because of high mechanical performances including reduced weight, the 3D composites from innovative 3D spacer fabrics are suitable in the construction of wind turbines (e.g. blades). Again, these structures could also potentially be used in designing of solar power producing lightweight rigid panels, for example, mounting the solar-cells (plates) on the faces, whereas the usage of hollow-chambers as supply-channels for electrical wires or for other devices. The resistance to pressure waves with the help of the energy absorption could be a further application in buildings and military vehicles for blast protection. Furthermore, the novel 3D spacer fabrics using high performance fibers show tremendous application possibilities in civil engineering (lightweight building and bridges) and in architectural design, especially as complex shaped fiber reinforced lightweight building panel systems. The cavity chambers would be suitable as medias, for instance, for maximum airflow, water-passage, drainage-systems, power-supply. Conversely, the spacer fabric structures are expected to show superior impact properties if the separation channels are equipped with the energy-absorbing materials. The bag-chambers could also be used to accommodate the appropriate equipment/ functional devices. In addition, spacer fabrics have the potential to be used as protective textiles for applications in the personal protection of the workplace and the sports equipment, medical applications, industrial textiles, for the protection of personal property, interior design, etc. The ease of using wide-spectrum of materials, fully flexibilities in structural diversifications, various reinforceing concepts along with cost-effective single stage manufacturing make the latest flat knitting technologies developed in this research extremely promising for the manufacturing of innovative 3D spacer fabrics for high-tech applications, especially in lightweight structures.

Chapter 9

Summary and Outlook

The material properties of textile reinforced composites can be specially customised for particular load situations by modifying the fiber architecture and material combinations and are best suited for lightweight applications. Novel 3D spacer fabrics consisting of surface fabrics connected with individual fabrics possess great potential as textile preforms in lightweight composite applications. However, flat knitting is one of the most flexible as well as advanced textile manufacturing processes and offers enormous potential to develop complex shaped load-adapted 3D spacer fabrics cost-effectively (competitive solution) for high performance composites.

In the scope of the presented research work, the flat knitting machines CMS 320TC and Aries.3 from the company of Stoll and Steiger respectively were selected as the modern flat knitting machines for the development of novel 3D spacer fabrics using examplar GF-PP hybrid yarns for thermoplastic composites. 3D spacer fabrics with varying the geometries were developed successfully using the innovative flat knitting techniques. This lead to various structural benefits (form follows force). In order to develop load-adapted 3D spacer fabrics, different innovative concepts for the integration of reinforcement yarns into knit structures were developed, where the multi-layer arrangement of reinforcement yarns (as warp and weft inlays) was considered to be suitable for high mechanical performances. With the aim of strengthening in the course direction, reinforcement yarns were successfully integrated directly into 3D spacer fabric structures separately as knit loops, tuck stitches and as weft yarns. The knit structures with integrated knit loops and tuck stitches were considered to be effective for high energy absorption in impact, whereas the weft yarns were expected to show high tensile strength and stiffness in the course direction. Within the framework of the development of multi-layered 3D spacer fabrics, different 3D tubular fabrics (with different arrangement of reinforcement yarns) were developed with the innovative flat knitting techniques and assigned high-tech applications. On the other hand, 3D spacer fabrics consisting of multi-layer reinforced plane layers (single weft & single warp inlays) and tuck stitch shaped connecting layers along with single axis curvatures were manufactured using the innovative flat knitting techniques. The intention of such multi-layer reinforcements was to increase the wall thickness of the composites to improve mechanical performance. Conversely, multi-layer reinforced 3D spacer fabrics consisting of individual surface and connecting layers, which are separately reinforced by 4 reinforcement layers (two warp and two weft inlays), including also the single axis curvatures were manufactured successfully using the highly innovative flat knitting technologies. With the purpose of monitoring the structural health of end products, the flat knitting technology was developed further for the creation of "sensor networks" by means of inventive integration of functional yarns into 3D spacer fabric structures during the manufacturing of the multi-layered 3D spacer fabrics. 3D thermoplastic composites were also effectively produced from flat knitted innovative 3D spacer fabrics (with vertical connecting layers) using the mechanical tools (for 3D thermoplastic moulding) developed in the

Collaborative Research Project 639.

In order to investigate the effect of fiber orientation on the mechanical properties of GF-PP hybrid yarns, 2D knit fabrics and 2D knit composites, reinforcement yarns were integrated into 2D knit structures individually as knit loops; tuck stitches; weft yarns; warp yarns; warp yarns and tuck stitches; weft and warp yarns; weft and warp yarns along with tuck stitches. The tensile strength of the reinforcement yarns after being pulled out from the 2D knit fabrics and of the 2D knit fabrics themselves were found to be better for warp and weft inlays, whereas these properties were only moderately improved with the tuck stitches. The mechanical properties of 2D composites consolidated from 2D knit fabrics were also investigated and seemed to be greatly affected by different arrangements of reinforcement yarns. Tensile and flexural properties were measured as superior in the course direction for weft yarns, in the wales direction for warp yarns and in both course and wales directions for biaxial inlays. In contrast, greatly improved impact properties were documented in the fiber oriented course direction for weft yarns, for tuck stitches and in the fiber oriented wales direction for warp yarns. Hence, the integration of reinforcement yarns as biaxial inlays into knit fabric seemed to be the most effective method, whereas the tuck stitch shaped and uni-directional reinforced knit structures (weft or warp inlays) can potentially be used in various applications. Therefore, based on the investigation of mechanical properties, the thermoplastic composites manufactured from the flat knitted multi-layered innovative 3D spacer fabrics are expected to show superior mechanical performances and considered to be more promising in high performance composite applications.

Additionally, the tensile strength of commingled hybrid yarn can be calculated directly using the model developed on the basis of the tensile strengths of component materials as well as the influence of the commingling process on their states. Again, the proposed model derived from the stitch geometry reported a highly significant resemblance between the experimental and predicted values and can be applied to calculate the tensile strength, portion of straight fiber in each direction as well as the specific weight of multi-layer reinforced knitted fabric. The developed mathematical model based on the rule of mixtures can be used efficiently to predict the tensile properties of multi-layer reinforced thermoplastic knit composites made of GF-PP hybrid yarns. However, considering the effect of integrated manufacturing processes (commingling to consolidation) on the state of tensile strengths of component materials, the thermoplastic consolidation process improves the tensile strength considerably in the composite form. The level of such improvement was up to 25% of total tensile degradation caused by the intermediate processes and it is considered to be the result of the filament-matrix interfacial bonding enhanced in composites.

Beyond the promising application trend in the area of lightweight composite structures, the novel 3D spacer fabrics produced with innovative flat knitting technologies can also potentially be used in different fields, for example, in textile reinforced concretes, architectural designs, energy sectors, protective textiles, industrial textiles and geo-textiles. Nevertheless, in order to manufacture extremely complex 3D spacer fabrics, further developments of the flat knitting technology could be carried out, for instance, for 3D spacer fabrics with multi-directional connecting fabrics (in x- and y-directions), double axis curvatures (in x- and y-directions) and with variable width within the respective connecting fabric (in z-direction). Moreover, the integration of continuous warp yarns into all connecting fabrics will improve the mechanical performances of connecting layers. In addition, the development of flexible and innovative warp-withdrawn as well as 3D take-down systems would be breakthrough advancements in the realization of a fully-automated flat knitting machine capable of manufacturing complex shaped innovative 3D spacer fabrics.

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