DEVELOPMENT OF WEFT KNITTED STRUCTURES WITH SELF-DIAGNOSTIC FUNCTION FOR PROTECTIVE APPLICATIONS

A thesis submitted by

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In partial fulfillment of the requirement for the degree of

Bachelor of Science

in

Textile Engineering

School of Engineering and Technology

NATIONAL TEXTILE UNIVERSITY, FAISALABAD

July 2023

DEDICATION

This Modest Effort is Dedicated to Our

Parents

&

Teachers

CERTIFICATE

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This thesis, written by **Muhammad Muzammil** and **Hassan Hameed** under the direction of **Dr. Habib Awais** and **Dr. Muzzamal Hussain** has been presented to and accepted by the Chairman, Department of Textile Engineering, in fulfillment of the requirement of the degree of Bachelor of Science in Textile Engineering.

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NATIONAL TEXTILE UNIVERSITY

STATUS CONFIRMATION FOR THESIS / PROJECT REPORT AND COPYRIGHT

ACADEMIC SESSION: 2019-23

TITLE OF THESIS / PROJECT REPORT:

Development of weft knitted structures with self-diagnostic function for protective applications

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ACKNOWLEDGMENT

Prevailing hands to brighter future we surely bow our head before Almighty Allah. All praise for Almighty Allah, most compassionate, source of knowledge and wisdom and creator of all the universe of logic, call us to think, about what is happening around us, as there is indication in them for believers. All our respect is for the Holy Prophet (PBUH) for enlightening our conscience with essence of faith and knowledge.

We surely admiral Department of Textile Engineering (NTU, Faisalabad) and our influential supervisor Dr. Habib Awais (Assistant Professor SET, NTU) and co-supervisor Dr. Muzzamal Hussain (Assistant Professor SET, NTU) and Mr. Shahzad Shafi (Quality Head, Midas Safety) who made onerous job for us by fine tuning through their standards and plight us from conventional life cycles. Their supervisor unveiled the technical aspects of knitting. Apprehending our research group was their courtesy for sure. Our solemn skills shined crediting him. Their apex experience and tactical way made us professional researchers in a broad spectrum leaving behind erstwhile textile developments in knitting technology. Their accordant efforts serge our focus on the crown than rock. We would like to acknowledge Pakistan Engineering Council for providing financial assistance under Financing of Final Year Design projects (FYDP). Thumps up for all who make their heart felt efforts for us in gaining pros and cons via their experiences.

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LIST OF ABBREVIATIONS

HPPE =High Performance Polyethylene
SHM =Structural Health Monitoring
CPU =Central Processing Unit
TENG =Triboelectric Nano-Generator
SC =Super Capacitors
TS =Textile Based Sensors
TATSA =Triboelectric All-Textile Sensor Array
FRBT =Fibre Reinforced Thermoplastic
CFY =Commingled Fiber Yarn
UTM =Universal Testing Machine
MMT =Moisture Management Tester
OMMC =Overall Moisture Management Control

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ABSTRACT

Self-diagnostic materials are significant due to their ability to detect and assess damage, enhancing structural integrity and safety. They enable early detection of issues, triggering timely maintenance actions and preventing catastrophic failures in critical protective gears. This proactive approach saves time, human life, and resources by reducing the need for manual inspections and periodic testing. Self-diagnostic weft knitted structures also contribute to increased reliability by continuously monitoring their own condition, minimizing unexpected failures. They find applications in diverse industries and offer versatile benefits, making them a promising technology for improving structural performance and safety. A significant research gap exists in the development of knitted protective fabrics with an additional capability for structural health monitoring. The utilization of textile structures, particularly knitted fabrics, has not been explored thus far. Therefore, it is essential to conduct research on the development of self-diagnostic fabrics using reinforced knitted structures. To address this research gap, self-diagnostic function fabrics were engineered on a V-bed flat knitting machine by inlaying Kevlar braid with a copper core. Additionally, rib structures such as Rib 1×1, Milano, and tubular rib were produced using HPPE (High-performance Polyethylene). By employing this approach, the research successfully fills the gap and demonstrates the potential of self- diagnostic knitted fabrics for enhanced protection. Cut resistance and comfort testing were performed, results showed 86% resistance to cutting of engineered fabrics, and electrical resistance graphs showed huge variations upon damages: verifying the self-diagnostic function. The self-diagnostic function was facilitated by the electrical conductivity of the copper core. The developed self-diagnostic fabrics provided real-time detection of structural deformations or breaches through monitoring electrical resistance. This feedback enables timely maintenance or replacement. Valuable insights were gained from reliability tests while maintaining the comfort parameters.

SUSTAINABLE DEVELOPMENT GOAL

The SDG that is linked with it is SDG-8 which is decent work & Economic Growth. In this project the development of weft knitted structures with self-diagnostic function for protective applications has been done. The conductive copper yarn is inlaid using kevlar braid in the rib knitted derivatives for measuring or sensing the mechanical and electrical changes in the fabric so it can be used to monitor the structural health of the products and the people that impact positive changes for decent work environment. The commercialization of this product can enhance economic productivity through technological innovation and advances the development of self-diagnostic protective textiles.

Chapter 1

Introduction and Literature Review

1.1 Background

"Textile" originates from the Latin term "texere," meaning "to weave," and it refers to a flexible material composed of various fibers, whether natural or synthetic, spun together like yarn [1] The history of textiles is intertwined with the development of human civilization. As human needs grew, textile manufacturing techniques advanced over time. In ancient times, people utilized tree bark, leaves, and animal hides to protect themselves from varying weather conditions and to provide modesty. These circumstances led to the invention of textile fabric and clothing manufacturing technologies.

Fabrics can be made from textiles by netting, looping, knitting, or weaving yarn that has been felted or spun from fibers to generate textiles. In the Middle East, fabric production first began in the late Stone Ages. According to historical records, textile manufacturing technology was invented around 7,000 years ago. Textile fabrics, which are two-dimensional structures, can be woven, knitted, or braided. These fabrics possess different mechanical and physical properties and serve as protective layers against climatic changes for the human body. Weaving the interlacement of two sets of yarns in the warp and weft directions is the oldest known technique for manufacturing textile fabric. It provides strength and durability to the fabric and allows for the creation of intricate patterns and designs [2].

Knitting, the interlooping of one or more sets of yarns, is the second oldest textile manufacturing technique. Knitted fabrics are known for their elasticity and flexibility. Notably, knitting technology can produce garments without the need for cutting and sewing, as the fabric is produced in a continuous loop [3]. In addition to weaving and knitting, other textile manufacturing techniques have gained popularity over time, including nonwoven fabrics, netting, and crocheting. The resulting fabrics can be cut and sewn to create various end applications, such as garments or clothing. Knitting technology stands out for its capacity to produce clothing directly without the need for cutting and sewing.

1.2 Knitting

Knitting is the second most popular textile fabric manufacturing technique. It is done by interlooping using one or two sets of yarns as shown in Figure 1.1. The process of interlooping is done either by hand or by a machine. Knitted fabrics have advantages over woven fabrics in terms of cost, process ability, inflexibility of design, and other performance parcels. Knitting can be divided into two types: weft knitting and underpinning knitting, depending on the direction of the yarn feeding and the direction of fabric conformation. If the direction of yarn feeding and the direction of fabric conformation are like one another, the type of knitting is also known as underpinning knitting, and if the two directions are vertical to one another, the knitting technique is also known as weft knitting .Out of these two types, weft knitting is extensively used in Pakistan and India [4].

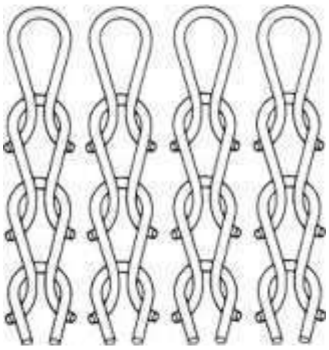


Figure 1.1: Interlooping of Yarns [5]

1.2.1 Weft Knitting

Weft knitting is a fabric manufacturing technique that involves the perpendicular feeding of yarn to the direction of fabric formation as shown in Figure 1.2. It is a type of knitting where the yarn is fed in a crosswise direction. The resulting fabrics are known as weft-knitted fabrics or simple jersey fabrics, and the machines used for this process are called weft knitting machines. These machines can be either flat or circular in shape. Latch needles are commonly used in weft knitting, and both natural and synthetic yarns can be utilized. In weft knitting machines, the finer gauge indicates a higher number of needles per unit area. Weft knitting machines can be classified as single bed or double bed, based on the arrangement of needle beds [6]. Cylinder or dial is equipped with grooves or cuts at regular intervals. The density of these cuts, known as the gauge of the machine, determines the number of cuts per unit length.

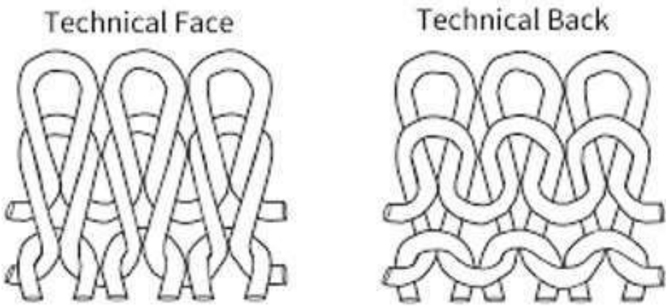


Figure 1.2: Weft Knitting Structures Face and Back [6]

1.2.1.1 Circular Knitting

The knitting technique known as circular knitting makes it possible to make a seamless cloth in the shape of a tube. Starting with a flat knitting-style cast-on, stitches are added, but the ends of the row are linked to create a circle. With this technique, a continuous tube of weft-knit fabric is created. When a tubular shape is not desired, the fabric can be cut along a single length, and the resulting open fabric can be used to cut out pieces for clothing patterns. This method is frequently used to create the conventional single-jersey T-shirt fabric. The primary fabric produced by circular knitting machines is the single jersey. It can be made from a variety of fibers, from conventional and organic cottons aimed at high-fashion markets to high-tech microfibers for active wear. The circular knitting machine's unique knitting cam and needle arrangement enable the creation of a variety of structures and stitches, including ribs, double jersey, purl structures, tuck stitches, and miss stitches. These differences can improve the fabric's aesthetic or practical value [7].

Figure 1.3: Circular Knitting Machine [8]

1.2.1.2 Interlock Knitting

Interlock knit fabric is a distinct variation of rib knit fabric. While rib knit fabric consists of rows that alternate between raised and lowered stitches, interlock knit fabric incorporates two rows of stitches instead of just one [9]. This is achieved by utilizing two rows of needles that intertwine to create the fabric. Due to the presence of these double rows, interlock knit fabric is also referred to as double-knit fabric. The interlocking of the rows occurs during the knitting process. The dual rows of interlock knit fabric contribute to its thicker composition compared to regular knit fabrics. This construction gives the fabric a firm feel while maintaining a soft and smooth texture. Furthermore, the thickness of interlock knit fabric enhances its absorbent qualities. As a result, interlock knit fabric offers both comfort and functionality, making it suitable for various applications [9].

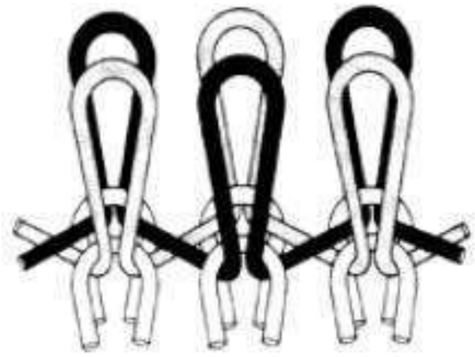


Figure 1.4: Interlock Knitting Design [9]

1.2.1.3 Flat Bed Knitting

There are two types of flatbed knitting machines single bed for plain or single jersey structures and double bed for rib and purl structures. Unfortunately, a flatbed machine with interlock gating is not available due to the difficulty in knitting with two sets of needles in each bed using cam carriages. But simply by removing one bed and its cam carriage from the combined unit, a double bed flat knitting machine may be quickly transformed into a single jersey knitting machine. Therefore, most commercial flatbed machines are supplied with two beds [10].

V-bed machines feature two diagonally positioned needle beds, forming an inverted V-shaped appearance. These machines have two ribs gated and are set at an angle of 90 to 105 degrees to each other. Flatbed purls or links-links machines, on the other hand, are primarily used to knit specialty items using double hooked latch needles. These machines allow one set of needles to be transferred to knit in either of the two directly opposed needle beds by utilizing a set of sliders in each bed.

Figure 1.5: Flat Bed Knitting Machine[11]

1.2.1.4 *Rib Knitting*

A rib knit fabric is characterized by visible and distinct perpendicular ribs on both the front and back sides. It is a reversible double-faced fabric. Rib knits are commonly used to create bands on t-shirt necklines, cuffs, hems, turtlenecks, and other similar applications. They are produced through a weft knitting method, incorporating purl stitches, and alternating knits on parallel rows.

Different variations of rib knits exist, such as 1×1, 2×2, 3×3, or 6×6, which refer to the sequence of knits and purl stitches in the fabric structure. The 1×1 rib knit consists of one knit stitch followed by one purl stitch, while the 2×2 rib knit pattern comprises two knit stitches and two purl stitches in a repeating sequence. Rib knits are versatile and suitable for sewing various garments and accessories like necklines, cuffs, turtlenecks, sweaters, rugs, mats, and home decor items [12]

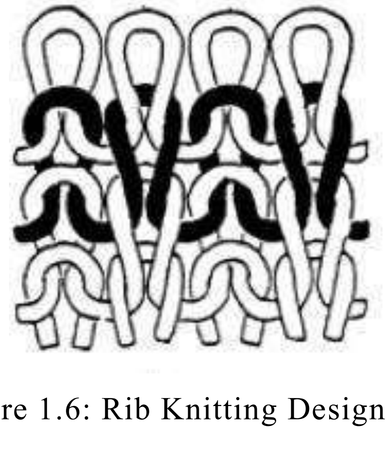


Figure 1.6: Rib Knitting Design [13]

1.3 Weft Knitted Rib Structural Derivatives

The weft knitted rib structures have the following derivatives.

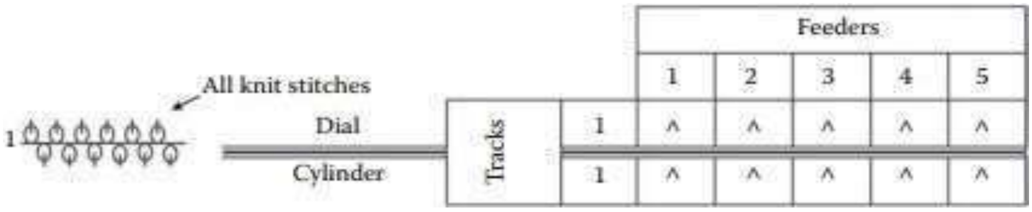
- Half cardigan
- Milano rib
- French pique
- Swiss pique

1.3.1 Structure with One Needle Type

Following are the rib knitted derivatives with one needle type:

1.3.1.1 Plain Rib

The plain rib structure (Figure 1.7) is a fundamental rib gating design used in knitting machines. It is characterized by all knit stitches, creating a fabric with prominent vertical ribs. The plain rib design has a single course repeat, meaning that the same sequence of stitches is repeated continuously across the rows as shown in Error! Reference source not found.. This simplicity in the design allows f or efficient production on knitting machines [14].

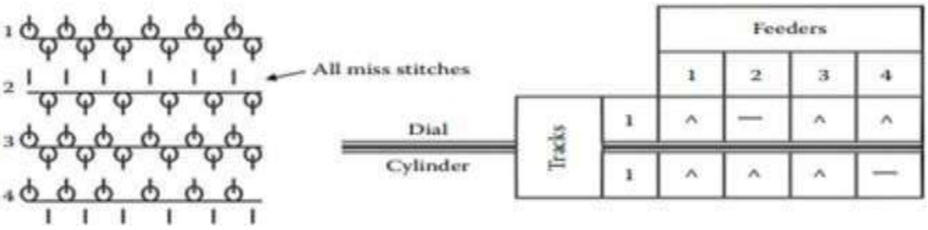


		Feeders				
Tracks		1	2	3	4	5
Dial	1	^	^	^	^	^
Cylinder	1	^	^	^	^	^

Figure 1.7: Plain Rib Design Notation [14]

1.3.1.2 Alternative Half Milano

Alternative half milano design (Figure 1.8) features a repeating structure composed of four courses, utilizing two stitch types: knit and miss. The knit stitch creates interlocking loops, while the miss stitch introduces intentional gaps within the fabric. To produce this design, at least one feeder is necessary to supply the yarn to the knitting machine. These elements combine to form a visually appealing pattern with endless creative possibilities [14].



		Feeders			
Tracks		1	2	3	4
Dial	1	^	—	^	^
Cylinder	1	^	^	^	—

Figure 1.8: Alternate Half Milano Design Notation [14]

1.3.1.3 *Cardigan*

Cardigan design (Figure 1.9) features a repeating structure comprising only two courses, involving knit and tuck stitches. The knit stitch creates interlocking loops, while the tuck stitch involves holding a stitch in place to create texture and patterns within the fabric [14].

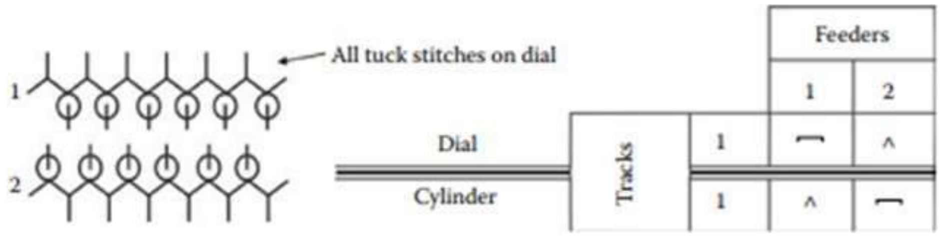


Figure 1.9: Cardigan Design Notation [14]

1.3.1.4 *Double Cardigan*

Double cardigan structure (Figure 1.10) indeed consists of a repeat of four courses, which is double the number of courses typically found in a cardigan design. The additional courses allow for more intricate and detailed patterns to be created within the fabric [14].

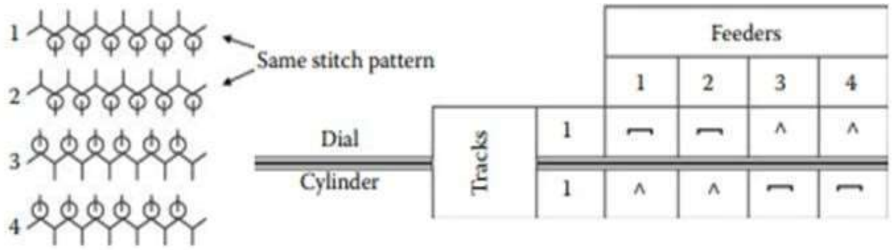


Figure 1.10: Double Cardigan [14]

1.3.1.5 *Double Half Cardigan*

In this design, the extended repeat of half a cardigan design allows for increased complexity and unique patterns within the fabric. With the repetition of four courses, the design showcases a combination of stitches and textures that enhance the overall visual appeal [14].

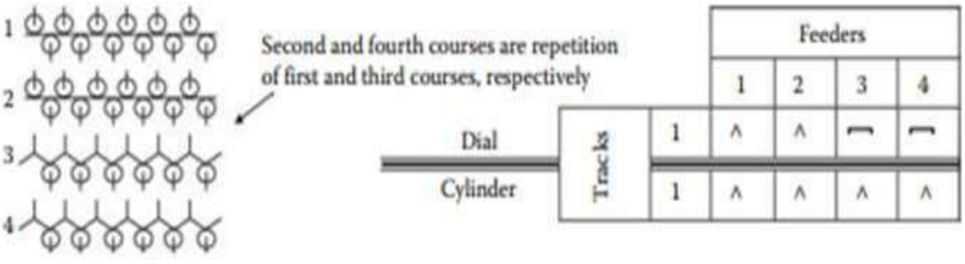


Figure 1.11: Double Half Cardigan Design Notation [14]

1.3.1.6 *Half Cardigan*

The half cardigan or royal rib design (Figure 1.12) creates an unbalanced structure by alternating between a 1×1 Rib on one course and a combination of tuck loops and reverse loops on another course. This interplay of different stitch types adds depth and texture to the fabric, resulting in a visually captivating and dynamic pattern [14].

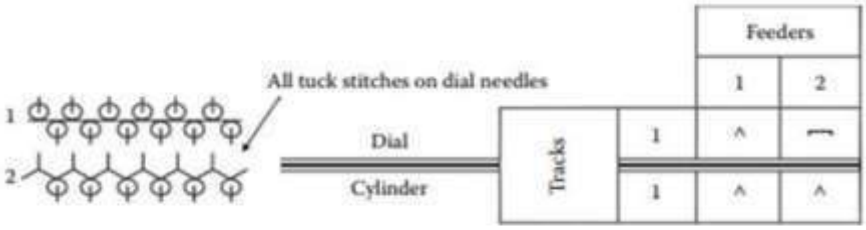


Figure 1.12: Half Cardigan Design Notation [14]

1.3.1.7 *Half Milano*

With a repeat of two courses or feeders, half milano design (Figure 1.13) showcases a balanced interplay between the knit and miss stitches. The knit stitch forms interlocking loops, while the miss stitch creates intentional gaps within the fabric, resulting in a visually captivating pattern [14].

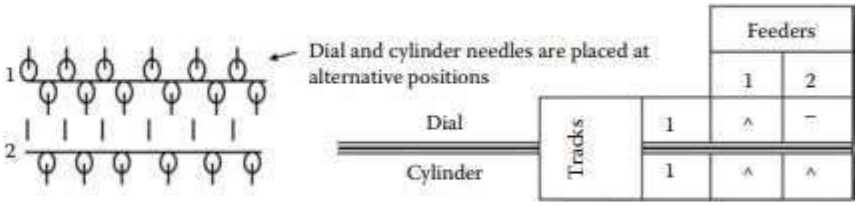


Figure 1.13: Half Milano Design Notation [14]

1.3.1.8 *Milano Rib*

The extended version of the half milano design (Figure 1.14) introduces an additional course, resulting in a total of three courses. This added course further enhances the complexity of the pattern, creating a captivating and visually appealing fabric with a combination of stitches and textures [14].

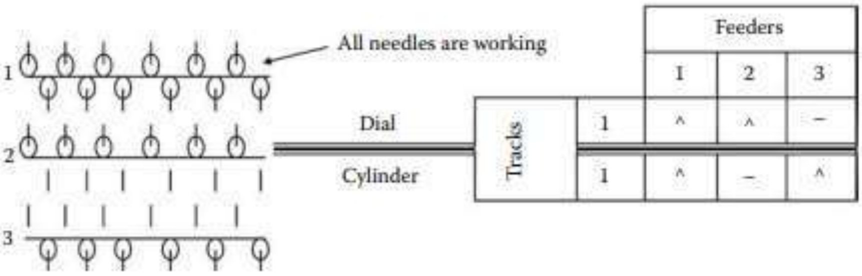


Figure 1.14: Milano Rib Design Notation [14]

1.3.1.9 Rib Ripple

The repeat of three courses in this design showcases a combination of two stitch types. Notably, courses 2 and 3 feature identical stitch patterns, contributing to the overall symmetry and consistency of the design as shown in Figure 1.15. This repetition adds visual harmony and balance to the fabric, resulting in a cohesive and aesthetically pleasing outcome [14].

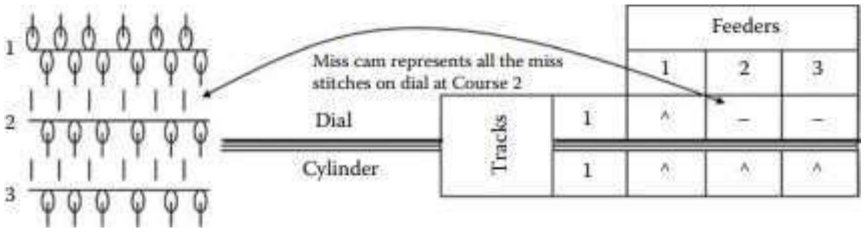


Figure 1.15: Rib Ripple Design Notation [14]

1.3.1.10 Ripple Cardigan

With a total of four courses in its repeat, this design highlights the significance of the last three courses, which share a common pattern. In these courses, both the dial and cylinder employ a tuck and knit stitch combination, resulting in a textured effect that adds depth and visual interest to the fabric. This repeated sequence of stitches creates a captivating and cohesive design throughout the knitted piece [14].

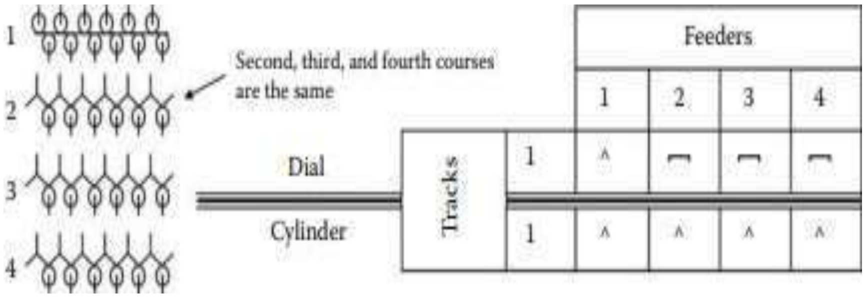


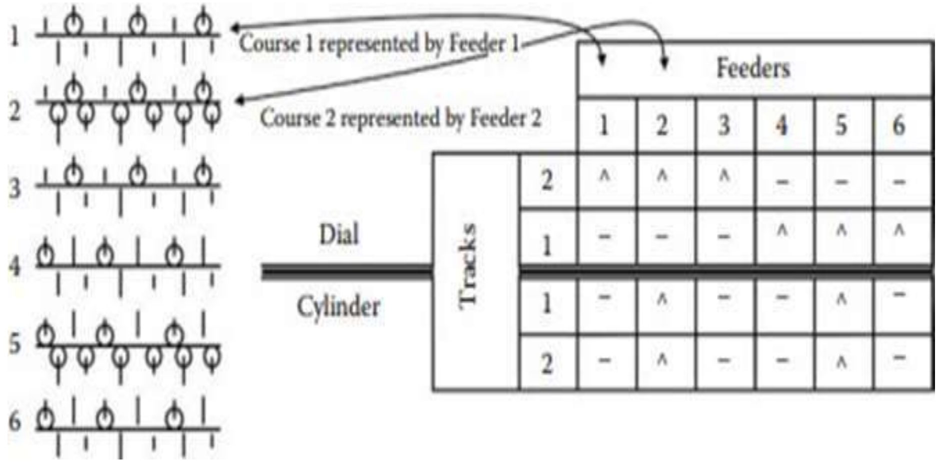
Figure 1.16: Ripple Cardigan Design Notation [14]

1.3.2 Structure with Two Needle Type

The category of designs that fall under this classification includes variations of the rib design, where two distinct stitch types are incorporated within the same course. Manufacturing such designs on a knitting machine necessitates the use of two tracks or needle types. The positioning of cams corresponds to the specific stitch types in each course. The needle repeat provides a general configuration guide for the placement of needles. On the cylinder side, the first needle of track 1 and the second needle of track 2 are positioned, while the same pattern is mirrored on the dial side [14].

1.3.2.1 *Belgian Double Pique*

With a repeat of six courses, this design showcases a rhythmic interplay of knit and miss stitches. The knit stitch creates interlocking loops, while the miss stitch intentionally skips a stitch, resulting in an open space within the fabric. This alternating combination of stitches adds texture and visual interest, creating a captivating pattern that repeats over the course of six cycles [14].

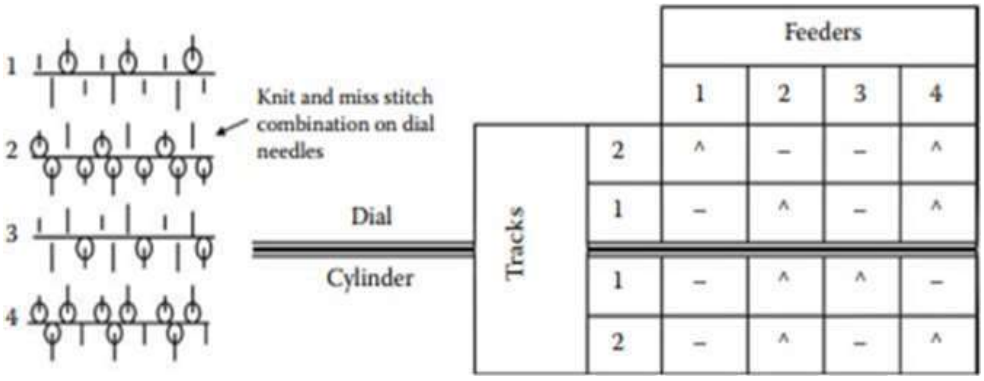


	Tracks	Feeders 1	2	3	4	5	6
Dial	2	^	^	^	–	–	–
	1	–	–	–	^	^	^
Cylinder	1	–	^	–	–	^	–
	2	–	^	–	–	^	–

Figure 1.17: Belgian Double Pique [14]

1.3.2.2 *Dutch Double Pique*

With the utilization of four feeders, this design showcases a repetitive structure formed by a combination of knit and miss stitches. The knit stitch interlocks loops, while the miss stitch intentionally creates gaps within the fabric, producing a visually interesting pattern. The incorporation of multiple feeders allows for a diverse range of possibilities and variations in the placement and arrangement of the knit and miss stitches, resulting in a dynamic and captivating design [14].

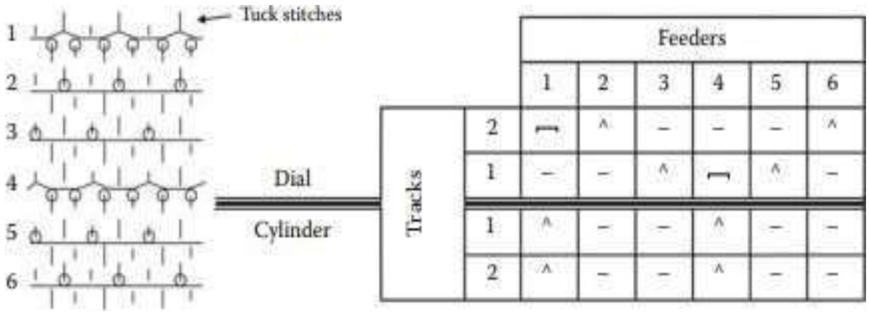


	Tracks	Feeders 1	2	3	4
Dial	2	^	–	–	^
	1	–	^	–	^
Cylinder	1	–	^	^	–
	2	–	^	–	^

Figure 1.18: Dutch Double Pique Design Notation [14]

1.3.2.3 *Fillet*

With a total of six courses, this design demonstrates a comprehensive showcase of all three types of stitches available. The inclusion of knit, miss, and tuck stitches allows for a diverse range of textures, patterns, and visual effects within the fabric. This intricate combination of stitches adds depth, complexity, and creative possibilities to the design, resulting in a captivating and visually dynamic knitted piece [14].

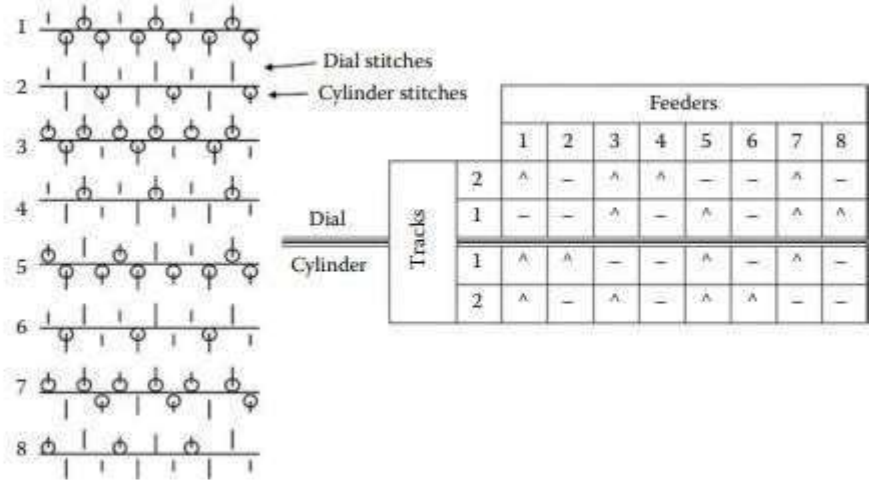


		Feeders					
		1	2	3	4	5	6
Dial	2	⊓	^	–	–	–	^
	1	–	–	^	⊓	^	–
Cylinder	1	^	–	–	^	–	–
	2	^	–	–	^	–	–

Figure 1.19: Fillet Design Notation [14]

1.3.2.4 *Flemish Double Pique*

The design has a total of eight courses. The design is formed by the knit and miss stitches at different stitching positions of dial and cylinder sides [14].



		Feeders							
		1	2	3	4	5	6	7	8
Dial	2	^	–	^	^	–	–	^	–
	1	–	–	^	–	^	–	^	^
Cylinder	1	^	^	–	–	^	–	^	–
	2	^	–	^	–	^	^	–	–

Figure 1.20: Flemish Double Pique Design Notation [14]

1.3.3 Drop Needle Design

The drop needle design on circular rib machine can be produced by removing the selective needle from dial and cylinder sides. The most common rib drop needle designs are Rib 2×1, Rib 2×2, Rib 3×2, etc. These designs give different aesthetics and functionalities to the fabric. The drop needle designs are produced by placing all the knit cams in a single track both on dial and on cylinder sides [14].

1.3.3.1 Rib 2×1

To achieve this effect, the design features two consecutive knit stitches on the cylinder side, followed by a single knit stitch on the dial side. Additionally, to create the desired pattern, every odd needle on the dial side is intentionally dropped, resulting in a distinctive visual element within the fabric. This deliberate manipulation of the needles adds texture and depth to the knitted piece, showcasing a unique and eye-catching design [14].

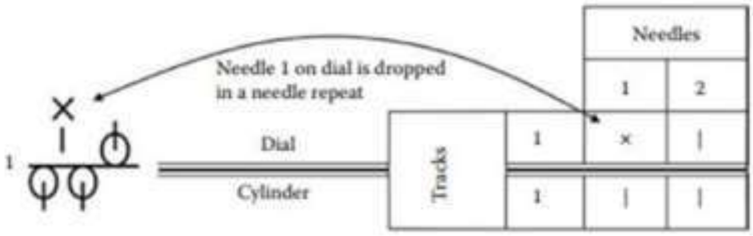


Figure 1.21: Rib 2×1 Design Notation[14]

1.3.3.2 Rib 2×2

In this design, each repeat consists of two knit stitches on the cylinder side followed by two stitches on the dial side. To achieve the desired effect, the third needle on the cylinder side and the very first needle on the dial side are intentionally dropped, as indicated in the needle repeat. These dropped needles add variation and texture to the fabric, creating an engaging and visually appealing pattern that repeats throughout the knitted piece [14].

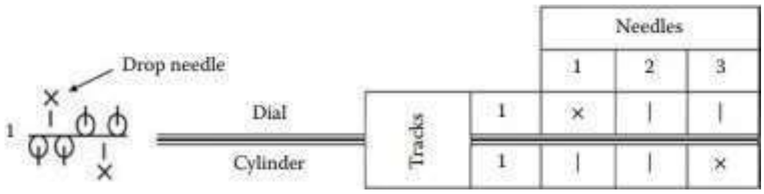


Figure 1.22: Rib 2×2 Design Notation [14]

1.3.3.3 Rib 3×2

In this design, each repeat comprises three stitches on the cylinder side followed by two stitches on the dial side. To achieve the desired effect, one needle is intentionally dropped on the cylinder side, while two needles are dropped on the dial side, as indicated in the needle repeat. This deliberate manipulation of the dropped needles adds texture and creates an intriguing pattern within the fabric, showcasing a visually captivating and unique design [14].

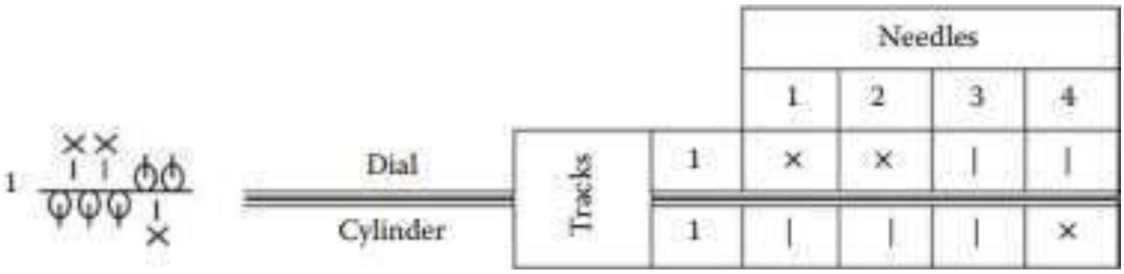


Figure 1.23: Rib 3×2 Design Notation [14]

1.3.4 Knitted Inlaid Structures

A technique for knitting with two needle beds in which stitches are moved from the active needles of one bed to the needles of the second bed to incorporate an inlay thread or yarn into the fabric as shown (Figure 1.24). This prevents the inlay from developing loops as it is interlaced or "woven" into the fabric. This enables materials that cannot be knitted to be incorporated into fabrics securely [15].

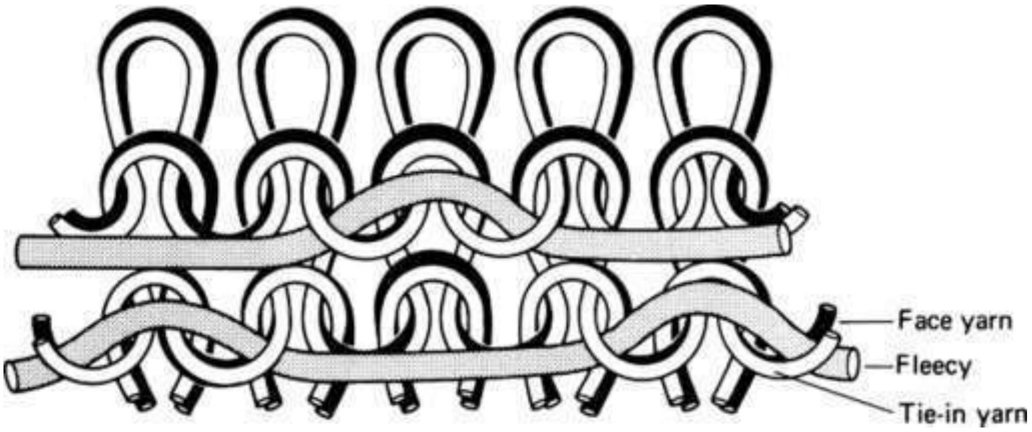


Figure 1.24: Inlay Yarn Description [15]

1.4 Warp Knitting

Warp knitting is a distinct type of knitting that originated as a machine-based technique ratherthan a hand-manipulated craft. Its development can be traced back to 1769 when Crane and Porter introduced it as a method of embroidery plating onto stocking fabric while being knitted on a hand frame. In warp knitting as shown (Figure 1.25), the yarn is fed parallel to the fabric selvedge into the knitting zone. This process forms vertical loops in one course before moving diagonally to the next course to continue knitting. As a result, the yarns create a zigzag pattern across thefabric's length. Each course comprises multiple yarns that contribute to the stitches, and multiple yarns are involved in creating each stitch within a wale [16].

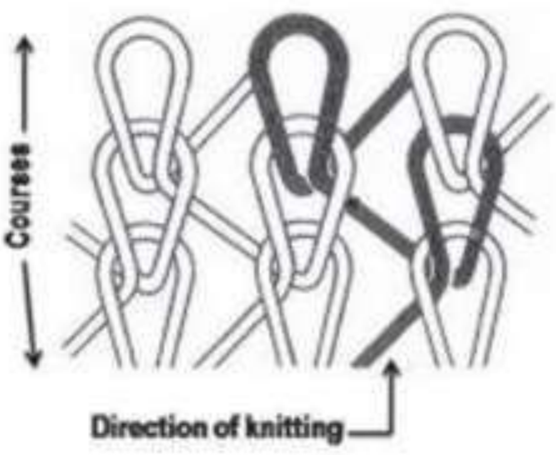


Figure 1.25: Warp Knitting Description [17]

1.4.1 Tricot Machine

Tricot is very common in lingerie and underwear. The fabric has across ribs on the back and fine lengthwise ribs on the right side. These materials have a soft, 'drapey' texture, some longitudinal stretch, and nearly no transverse stretch, among other characteristics. Tricot machines (Figure 1.26) include 2 guide bars tricot, 3 guide bars tricot, and 4 guide bars tricot machine [18].

Figure 1.26: Tricot Machine [19]

1.4.2 Milanese Knit

Milanese fabric, known for its strength, stability, smoothness, and higher price point, was traditionally used in high-quality lingerie. This type of knit fabric is constructed by weaving two sets of yarn diagonally, resulting in a vertical ribbed pattern on the face side and a diagonal structure on the reverse side. These characteristics contribute to its lightweight nature, smooth texture, and resistance to runs. However, Milanese fabric has become largely outdated in modern times [20].

1.4.3 Raschel Knit

In 1855, Redgate introduced an innovation by combining the circular loom principles with those of warp knit. Utilizing this machine, a German firm started producing shawls called "Raschel," named after the renowned French actress Élisabeth Félice Rachel. Subsequently, in 1859, Wilhelm Barfuss further improved the machine, leading to the creation of raschel machines.

During the 1870s, the Jacquard apparatus was incorporated into these machines. Raschel machines demonstrated superior speed compared to Leavers machines and proved highly adaptable to synthetic fibers like nylon and polyester, which emerged in the 1950s. As a result, most modern machine-made lace is produced using raschel machines [21].

1.5 Braiding

Braid (Figure 1.27) is a type of narrow fabric created by intertwining three or more than three yarns or fabric strips, resulting in either a flat or tubular structure. It serves various purposes, including decorative trimmings, belts, and it can also be sewn together to craft hats and braided rugs. The term "plaiting" often used interchangeably with braiding can have a more specific meaning, referring specifically to braids made from materials like rope and straw [22].

Figure 1.27: Braiding [22]

The process of interlacing three or more yarns or bias-cut fabric strips together so that they cross each other and are arranged diagonally to create a narrow strip of flat or tubular fabric by hand or by machine is known as braiding. The term "plaiting" is typically used when using materials like rope or straw.

1.5.1 Inlaid Braided Structures

The inlaid braided structure (Figure 1.28) is a specific type of textile structure that incorporates braiding techniques, wherein a third yarn is introduced as an inlay.

Textiles created using braiding techniques for composites typically involve the interlacing of two or more sets of yarns. Biaxial braids specifically utilize two sets of yarns, while triaxial braids incorporate an additional third set of axial yarns.

Figure 1.28: Inlaid Braided Design Description [23]

1.5.2 Braiding Structures Types

Different yarn systems are interlaced to create braided textile constructions in a tubular shape. Three primary forms of braided structures are as follows:

- Diamond
- Regular
- Hercules

1.5.2.1 Diamond Structures

The diamond structure is achieved by having yarns cross alternately over and under other yarns in opposite directions, with a rotation of one by one. This rotation can be adjusted to two by two or three by three to create the other two structures. Among the three types, the diamond structure offers the highest stability, while the hercules structure exhibits the lowest stability [24].

1.5.2.2 Regular Structures

To create a regular structure in braiding, it is essential to maintain consistent tension on all yarns throughout the process. One common method to achieve this is by attaching weights to the ends of the yarn. In cases where hand braiding is done for shorter lengths, a practical approach is to utilize small bags filled with sand. This allows the braider to conveniently adjust the weight of each bag by adding or removing sand as needed to meet specific requirements [24].

1.5.2.3 Hercules Structures

Hercules braided structures are known for their dense and intricate interlacing pattern, which contributes to their exceptional strength and durability. These structures are highly robust and resistant to wear and tear, making them well-suited for applications that require high tensile strength. Industries such as aerospace, automotive, and sports equipment often utilize Hercules braided structures due to their reliability and ability to withstand demanding conditions [24].

1.6 Structural Health Monitoring

Structural health monitoring (SHM) is a field that focuses on observing and analyzing engineering structures, such as bridges and buildings, over time.

1.6.1 Self-Diagnosis

Self-diagnosis is the process of finding or diagnosing one's own medical issues. Medical dictionaries, books, online resources, past experiences, or recognizing symptoms or physical signs of a condition a family member has had may all be helpful.

1.6.2 Structural Health Monitoring

Structural health monitoring (SHM) is a field that focuses on observing and analyzing engineering structures, such as bridges and buildings, over time. It involves periodically collecting response measurements to monitor any changes in the material and geometric properties of these structures.

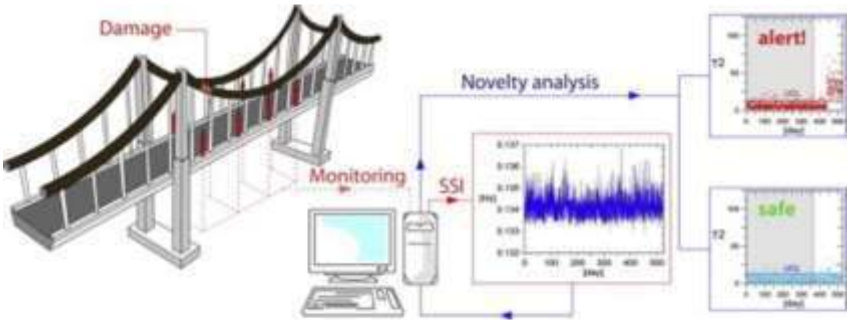


Figure 1.29: Structural Health Monitoring Description using Sensors [25]

SHM is an evolving technology that encompasses the development and application of integrated sensors as shown in above Figure 1.29, aiming to facilitate monitoring, inspection, and damage assessment. By employing advanced signal processing techniques, the data collected through SHM can inform maintenance actions as needed, ensuring timely and appropriate interventions [25].

1.6.3 Intelligent Devices

The term "intelligent" refers to devices that leverage computational power to enhance their performance. These intelligent devices (Figure 1.30) are not inherently integrated into the material itself but rather function to sense specific stimuli related to the material through singular processing techniques. They are designed to detect and respond to stimuli using computational capabilities, enabling them to augment the overall performance of the material [26].

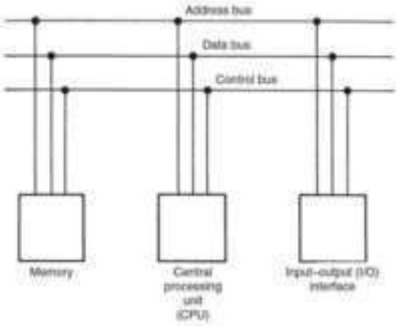


Figure 1.30: Elements of Intelligent Devices [27]

Intelligent devices consist of a microcomputer that comprises three key elements. Firstly, there is the memory component, which stores the data being processed by the central processing unit (CPU) temporarily and retains data for which responses are needed. The CPU processes the received data based on the guidelines stored in memory and makes decisions accordingly. The input-output interface is responsible for receiving input data and generating signals as output. Smart sensors are utilized for fault diagnosis in materials. These sensors possess the capability to locally process data and generate responses without relying on a central controller. They continuously monitor input data for potential faults and produce appropriate signals or alarms. To monitor a different type of fault, an additional sensor is required. Self-diagnostic sensors often operate by sensing capacitance and resistance values of materials and generating suitable responses based on these measurements. They provide a localized approach to fault monitoring and response generation [27].

1.6.4 Piezoelectric Materials

Piezoelectric materials possess the remarkable ability to generate electrical voltage impulses when subjected to mechanical stress. Conversely, when an electrical voltage is applied to piezoelectric materials, they undergo a positive volumetric strain. These unique properties make piezoelectric transducers highly valuable in sensing applications. Piezoelectric materials are commonly employed for reinforcement purposes in composites. They are connected to external circuits, allowing the measurement of the voltage generated in response to mechanical stimuli. By monitoring the voltage values until the breaking point, this information is fed into a sensor that triggers an alarm when predetermined thresholds are reached, ensuring appropriate user notification. Piezoelectric materials commonly used for their unique properties include polymer, quartz (SiO_2), and Rochelle salt ($NaKC_4H_4O_6$–$4H_2O$). However, due to the low voltage generated by piezoelectric materials, it can be challenging to detect and sense that voltage directly. Therefore, an alternative approach is employed for self-diagnosis of materials. In this technique, an input voltage is continuously applied to piezoelectric transducers attached to the target material. As a result, guided waves are generated within the material and propagate through it. A sensing mechanism is also implemented on the material to detect the behavior and path of these waves. If any damage occurs to the material, the traveling waves are disrupted, and the sensor detects deviations from the original wave properties. Consequently, an appropriate signal, often an alarm signal, is generated to indicate the presence of damage in the material [28].

1.6.5 Nanomaterials

Nanomaterials (Figure 1.31) are characterized by their nanoscale features, which enable them to exhibit unique and novel properties compared to the same materials lacking these nanoscale characteristics. These properties can include mechanical, thermal, chemical, and more. One application of nanomaterials in self-diagnosis is through the induction of conductive properties in nanofibers. Researchers have explored the use of nanomaterials such as nano carbon black and carbon fibers in various studies related to the self-diagnostic capabilities of nanomaterials. It has been observed that these materials undergo changes in resistance when subjected to external forces, making them suitable for practical applications in self-diagnosis. These advancements pave the way for utilizing nanomaterials to develop innovative self-diagnostic systems [29].

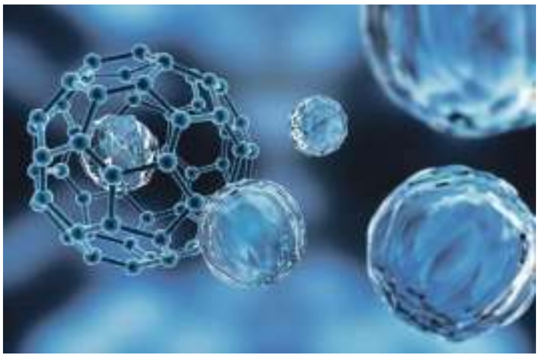


Figure 1.31: Nanomaterials Microscopic Image [29]

1.7 Literature Review

Adeel Abbas et al. [30] focused on the development of knitted reinforcement structures to introduce self-diagnostic properties in knitted reinforced composites for structural health monitoring purposes. The research aimed to correlate mechanical damages with changes in electrical resistance values, utilizing the conductive nature of the reinforcement materials. The materials used in the study included 100% polyester, carbon, and unsaturated polyester. Various experimental variables were investigated, including the stimuli layer and inlay pattern. The knitted structures employed in the study were 1×1 rib, 3×1 rib, 6×1 rib, and 9×1 rib. Tensile testing and flexural testing were performed to evaluate the properties of the composites. Special testing techniques, such as using nails on carbon and a computerized voltmeter, were employed. The study found that during the knitting of the reinforcement, knitted reinforced composites could be given self-diagnostic properties. An external monitoring device might be used to measure the electrical resistance of the inlaid yarns in real-time. Furthermore, using conventional laboratory testing techniques, it was possible to evaluate the electrical resistance of the knitted reinforced self-diagnostic composite easily and affordably. Overall, this research lays the groundwork for adding self-diagnostic capabilities to knitted reinforced composites, pointing to potential future applications.

In a study conducted by Kia Dong et al. [31] the focus was on the development of a self- charging knitting power textile with high stretch ability. The challenge addressed was the need for power devices in stretchable and multifunctional wearable electronics to be portable and possess comparable stretch ability. Commercial 3-ply-twisted stainless steel/polyester fiber yarn, a bundle of carbon fiber, a circular plastic tube, and a circular acrylic plate were among the materials utilized in the investigation. Real-time data capture, human movements, and mechanical tensile testing were used to assess the textile's characteristics. The development of a highly flexible and machine-washable self-charging knitted power textile was successfully reported by the researchers. This fabric's integration of a triboelectric nano-generator (TENG) and supercapacitors allowed for simultaneous energy storage and biomechanical energy harvesting. The power textile was created using the weft-knitting technique and showed significant levels of elasticity, flexibility, and stretchability, enabling it to accommodate intricate mechanical deformations. By converting energy from human actions, the completed knitted power textile proved the ability to sustainably power wearable devices like calculators or temperature-humidity meters. Stretchable multipurpose power sources are being developed thanks to this research, which also creates opportunities for wearable electronics.

In a study conducted by Keyu Mang et al. [32] the focus was on self-powered personalized health care using a textile-based sensor system. The researchers aimed to develop a textile- based sensor system with an artistic design that could be used for wearable biomonitoring and internet-based interaction. Silver-coated conductive cloth and a piece of commercial polyester textile were among the materials utilized in the investigation. A circular form was stitched together using dielectric nylon yarn and polyester-metal hybrid fiber. Testing was done using a dual-range force sensor, a Stanford low-noise current preamplifier (Model SR560), and SEM imaging of the polyester-metal. To process human pulse wave impulses in real-time, wirelessly transmit the data, and show the patient's health information through a smartphone application interface, a wireless biomonitoring system was created. Even in the presence of body movements, the WBS successfully diagnosed obstructive sleep apnea-hypopnea syndrome throughout a whole night of sleep. An important step forwards in the creation of a body area network for individualized healthcare on the Internet of Things era is the textile-based wireless biomonitoring system. Through internet connectivity, it provides a promising option for future personalised health care and allows for timely monitoring and interaction.

In their research, Wenjing Fan et al. [33] focused on epidermal physiological signal monitoring using a machine-knitted washable sensor array textile. They created a highly sensitive triboelectric all-textile sensor array (TATSA) to measure even the slightest pressure on the skin. Using conductive and nylon yarns and a whole cardigan stitch pattern, the TATSA was knitted. The researchers developed a customised intelligent health monitoring system to evaluate the effectiveness of the TATSA in real-time and remote health monitoring. This device continuously collected and recorded physiological data for the evaluation of sleep apnea syndrome and the analysis of cardiovascular disease. Commercial one-ply Terylene yarns were treated with stainless steel fiber electrodes, and a full cardigan design was used. Washing tests, assessments of dual-range force sensors, measurements of sinusoidal pressure signals, and evaluations of pulse wave velocity were all carried out. Different respiratory signals were successfully identified by the TATSA using the complete cardigan stitch, and the signals were shown on a mobile device. This study made a substantial advancement in the field of wearable textile electronics for epidermal physiological signal monitoring by introducing a comfortable, effective, and user-friendly method to record human pulse and respiration.

Marcela Ferrándiz et al. [34] focused on the development of weft-knitted sustainable functional textiles using naturally occurring polymer fibers. The researchers assessed the potential of chitin, SP, and coir fibers, derived from agricultural and food wastes, to produce functional fabrics. Chitin fibers, coir fibers, and SP fibers were utilized as materials for the study. Weft-knitted fabrics were created by spinning these fibers into yarn and constructing fabrics with consecutive rows of intermeshed loops in a horizontal manner. Each row of loops was built upon the prior loops in a consecutive fashion. The researchers performed various tests following the Kawabata system, including Koshi, Numeri, and Fukurami tests, to assess the properties of the fabrics. Antimicrobial tests and comfort assessments were also conducted. The study demonstrated that natural fibers, such as chitin, SP, and coir, have the potential to be used in the production of functional fabrics. The fabrics exhibited favorable properties, as indicated by the THV parameter, which showed adequate values for SP and chitin within the average range. In comparison, the cotton/polyester fabric only met the requirements for winter-autumn clothing with its THV value falling within the good range. This research highlights the development of sustainable functional textiles using naturally occurring polymer fibers, offering potential solutions for environmentally friendly fabric production.

Raluca Maria Aileni et al. [35] focused on the development of wearable sensors for healthcare applications. The study consisted of three main parts: In the first part, a knitted textile structure with embedded sensors was used to build a 3D wearable device. A textile sample for breathing monitoring was created and examined by the researchers using an elastic fabric with a polymer optical fibre. The elastic fabric of the textile sample had a silica optical fibre woven into it using an industrial crocheting technique. A fibre Bragg grating sensor and a macro bending sensor were incorporated into the design and embroidered onto the fabric.

The sensor model for electrical and mechanical simulations was the subject of the study's second section. Using optical fibres, phase-based and wavelength sensing were carried out. Additionally, the researchers created a simulation for a 3D knitted framework that permitted the placement of sensors. A linkage system for support and sensors was the subject of the study's concluding section. The Kawabata system was used to assess the knitted structure's compression capabilities. The findings showed that knitted structures have more flexibility than woven structures. This finding highlighted the suitability of wearable devices as they can be modeled to fit human body parts more effectively. Overall, the research by Aileni et al. [35] demonstrated the development of wearable sensors using knitted textile structures with embedded sensors. The study explored the use of polymer optical fibers and optical sensors for healthcare monitoring. The findings emphasized the advantages of knitted structures in terms of elasticity and customization for better integration with the human body.

Fangueiro R et al. [36] developed a high-performance single layer weft knitted structures for cut and puncture protection to be used as protective clothing. There is a clear need for the creation of flexible materials that can safeguard workers in various working environments without sacrificing their comfort. High performance fiber-based yarns, including para-aramid, ultra-high molecular weight polythene, high tenacity polyamide, high tenacity polypropylene, and high tenacity polyester, were the materials employed. The created variables included single jersey, crepe, and moss tuck stitch weft knitted textiles. Conical and knife probes were used for the punctures, and the samples used for the tests were evaluated in accordance with EN 388. The maximum knife puncture resistance is seen in the para-aramid crepe structure.

Lidor Yousef et al. [37] developed a smart self-sensory textile for structural health monitoring based on carbon. By physically loading two textile reinforced concrete beams, one using a monotonic loading process and the other using a cyclic loading procedure, the study aims to illustrate the engineering gauge factor idea and the structural health monitoring procedure. The materials utilised for this project included AR-glass rovings, AR-carbon rovings, a wire ferrule, connections, Sika Grout, and water. As samples, warp knitted grid TRC beam specimens made of carbon were created. Utilising the four points bending method in a displacement mode, mechanical loading tests were conducted. a comparison of the two beams' structural and electrical responses. The validation and proof of the engineering GF's sensory idea. The method for using sensory carbon roving to check the structural health is described.

Niclas Wiegand et al. [38] analyzed two sensor yarns for structural health monitoring. In-situ monitoring sensors are included in the fabric during the textile production process using various wire and fibre materials to prevent flaws and to enable an early warning before breakage. Therefore, the orientation of the reinforcement material is used to measure the mechanical load. Hybrid yarns, air-textured commingled yarn, TohoTenax, silane coupling agent, maleic anhydride polypropylene film, deionized water were the materials used for this experiment. The weft knitting process was used to make the textile using knit, tuck and loop threads mentioned above. The final fabrics for testing were made in a platen press process, fabrics without sensors were also made. Electrical resistance is measured during textile manufacturing process for testing. The outcomes show that the mechanical impact delivered to the sensor yarns during integration is the primary factor degrading the CF-sensor yarns' conductivity.

E.Häntzsche et al. [39] studied character-based carbon fiber-based strain sensors for structural-health monitoring of textile-reinforced thermoplastic composites. The focus of the paper is on efficient online measurement technology for non-destructive and continuous monitoring of infinite glass fibre reinforced thermoplastic (FRTP) composite structures using the many possibilities of textile process technologies for the design and one-step integration of one- and two-dimensional sensor structures. Filament yarns made of polythene terephthalate (PET), a hybrid yarn having a CFY core and a PP sheath, were employed. Commingled glass fibre (GF)-PP hybrid yarn constructions are knitted and woven with CFYS or by employing the TFP process, embroidery on the knitted constructions' surface. using pure CFY in cyclic tensile testing as strain sensors. The tests included resistance load per unit length, tensile load cycles, and pure CFY serving as a strain sensor's sensory behaviour under tensile stresses. In order to adjust and guarantee an appropriate signal response characteristic of the CFY acting as a strain sensor, adequate structural linking or interlacing must be chosen. This is because of the requirements on the measuring task, or rather the structural-health monitoring, such as accuracy.

MMB Hasan et al. [40] studied the early prediction of failure of textile reinforced thermoplastics using hybrid yarns. The purpose of the experiment was to study the effects of hybrid yarns utility in structural health monitoring. The friction spinning method was used to create the core-sheath hybrid yarns from glass filament yarn (GFY) and steel fibres, which are useful for predicting failure. The test used a hydrogel membrane, knitted electrodes, and two stainless steel wires wound around a viscose textile thread. Biaxially reinforced knitted fabric (90°/0°) was the construction employed. During testing, the steel fibre content was changed, and various electrical readings were recorded. Tensile test, strain sensitivity, and electrical resistance of FS hybrid yarns in composites. Embedded FS yarns in composites were tested under tensile loading using DIN 3341, tensile strength was measured using a Zwick type Z 100 device, and TS and current were tested using a Fluke 8846A precision multi-meter.

The findings demonstrate that there is no discernible difference between the FS yarns in terms of breaking force or elongation after tensile testing. Hybrid yarns are better suited to foresee deterioration before breakage than the other thermoplastic composite structural health monitoring options, such as metal ductile filaments and metal twisted yarns.

Yiska Goldfeld et al. [41] studied the use of hybrid carbon-based textile-reinforced concrete elements with self-sensing capabilities to identify wetting events within the cracks. Carbon fiber rovings, polymer sheets, glass fiber rovings, stainless steel–based TRC beam were used in the in Warp-knitted grid structure textile layer including six longitudinal (0°) glass fiber rovings and three longitudinal carbon rovings were used. The transverse (90°) rovings are all made of glass fibers. In the experimental procedure electrical short-circuiting of two consecutive carbon rovings was done using two opposite out-of-phase Wheatstone bridges. This process involved carbon rovings using an AC setup where the test setups were installed to get different results. Splicing of integrated optical fiber was analyzed using Mz interferometer, while MFC 3000 was used for tensile tests. The functionalized carbon reinforcement samples showed comparatively low hysteresis and drift and a robust and dependable connection between applied force and measured elongation. Even if the conductivity of dry concrete is generally low, resistance and less so capacitance influence the linkages between the rovings and the electrical readings. The results show a change in the electrical response because water has seeped into the damaged zones.

Kort Bremer et al. [42] studied structural health monitoring with the help of textile reinforced structures embedded with optical fiber sensors. The study's objective was to keep track of SHM variables including strain and cracks while also serving as a procedure that enforced structural strength. Using Mach-Zehnder interferometric and optical attenuation measurement techniques, respectively, the sensor performances of the two systems are evaluated. Using a tensile testing machine and carefully increasing the applied tension, various FCS samples were subjected to variable elongation for this purpose. The applied force and measured length change showed a strong connection. The biaxial knitted optical glass fibre grid was employed. Tensile testing, sensitivity to stresses testing, and force transferred between the carbon structure and the optical fibre of the FC test were carried out. Utilising a Mz interferometer, integrated optical fibre was spliced. On MFC 3000, the tensile test was conducted. The functionalized carbon reinforcement samples showed comparatively low hysteresis and drift and a robust and dependable connection between applied force and measured elongation. The produced FCSs exhibit a linear response to applied longitudinal forces with a negligibly large amount of hysteresis and drift (0.0033 mm/N (1.4%)), compared to a conventional derivation of 0.042 mm/N for 1D FCS.

M.A. El-Sherif et al. [43] studied smart and intelligent structures in diagnostics and health monitoring. The purpose of the study was integrating lightweight miniature sensors and networks into smart structures that will provide advantages for many applications. It also focuses on forming the basis for the development of intelligent systems for health monitoring. The optical fiber, fiber network, textile structure. The variable used was structure (plain, twill, and satin weave). Tensile test, electrical and optical sensor test (Photoelectric) and air grip test were performed. Experimental work was carried out for the validation of the MPD technique in measuring quasi-static and dynamic strains in textile structures. The fbg was based on fiber Bragg grating sensors, and the second type of the sensors is based on the MPD sensor. A light source and from the other end to a photo detector and an RF transmitter were used. Wireless remote sensor capability can be applied to the smart shirts for continuous health monitoring by the patient physician from a remote location. The value of the MPD technique in smart structures applications, where the requirement of miniature structures and sensitivity are of great importance, has been successfully demonstrated through these smart textiles.

1.8 Research Problem

Conventional knitted protective clothing does not have their health sensing capabilities which leads to severe accidents after products service failure. So, load limits are to be measured for developing alarming systems in self- diagnostic fabrics before specifying their applications.

1.9 Research Gap

There is not any significant published work on knitted protective fabric development with an additional structural health monitoring capability. Use of textile structures specially knitted fabrics hasn't been experienced so far. That is why research of self-diagnostic fabric is vital using knitted structure's reinforcements. Since now integrated systems are being used for structural health monitoring of fabric which often leads to wrong alarm and damages in fabric, hence self-diagnostic properties are obliged within the fabric.

1.10 Research Aim

The aim of the study is to engineer weft knitted structure offering self-diagnostic function or structural health monitoring.

1.10.1 Specific Objectives

Research specific objectives are as following:

- To develop weft knitted inlaid fabric for protective applications i.e., cut resistance.
- To evaluate the efficacy of engineered fabric towards self-diagnostic function and comfort parameters.

Chapter 2

Materials and Methods

2.1 Materials

Keeping the basic aim of research material type used for composites and reinforcements construction will of only one type while the courses in which yarn is inlayed as the reinforcement i.e., structure must be varied. For the research following materials has been utilized:

- Kevlar
- HDPE
- Copper

2.1.1 Kevlar

Kevlar is a strong, heat-resistant synthetic fiber, related to other aramids such as Nomex and Technora. Kevlar is known for its exceptional strength, light weight, and resistance to impact, penetration, and chemicals. It is widely used in ballistic body armor, aerospace components, automotive parts, and protective clothing. Its high strength-to-weight ratio and thermal stability make it a versatile material for various applications. Furthermore, Kevlar exhibits excellent thermal stability and does not melt or support combustion. It retains its strength and integrity even at high temperatures, which makes it valuable in applications where heat resistance is critical.

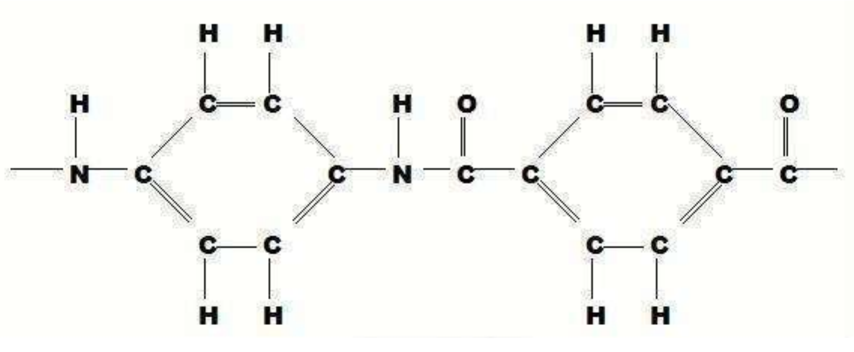


Figure 2.1: Kevlar Chemical Formula

2.1.2 HPPE

HPPE, which stands for High-Performance Polyethylene, is an advanced synthetic fiber known for its exceptional strength, durability, and cut-resistant properties. It is a type of polyethylene that has been engineered to provide superior performance in demanding applications. HPPE fibers are incredibly strong, often surpassing the strength of traditional materials like nylon or polyester. Pound for pound, HPPE is several times stronger than steel, yet much lighter in weight. This high strength to weight ratio makes it an ideal choice for applications where strength and reduced weight are critical, such as in high-performance ropes, cables, and industrial lifting slings. One of the notable properties of HPPE is its excellent cut resistance. It has a high level of resistance to sharp objects, making it valuable in applications where protection against cuts and abrasions is essential. HPPE fibers are commonly used in the manufacturing of cut-resistant gloves, sleeves, and protective clothingfor workers in industries like manufacturing, construction, and glass handling.

HPPE also exhibits good chemical resistance, with resistance to many acids, bases, and solvents. This property makes it suitable for use in environments where chemical exposure is a concern, such as in the chemical processing industry.

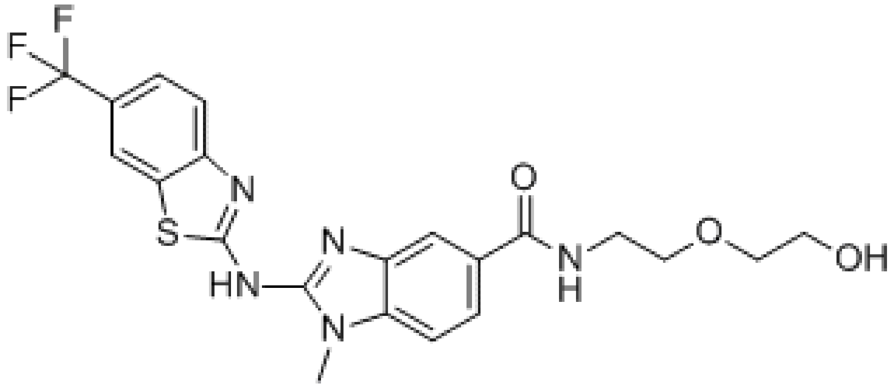


Figure 2.2: HPPE Structural Formula

2.1.3 Copper

Copper is a reddish-brown metal known for its excellent electrical and thermal conductivity. It is one of the most widely used metals due to its numerous desirable properties. Copper has been used by humans for thousands of years and is valued for its versatility and durability. One of copper's primary characteristics is its exceptional conductivity. It produces electricity more effectively than any other non-precious metal, making it essential for electrical wiring and transmission of power in various industries. Its high thermal conductivity also makes it suitable for heat exchange applications, such as in cooling systems and heat sinks. Copper is highly malleable and ductile, meaning it can be easily shaped and drawn into wires or hammered into thin sheets without breaking. This property makes it a preferred material in plumbing systems, roofing, and electrical connectors. It can also be alloyed with other metals to enhance specific properties, such as strength or corrosion resistance. Another advantage of copper is its resistance to corrosion. It forms a natural oxide layer on its surface, which protects it from further oxidation and deterioration. This resistance makes it suitable for outdoor applications, such as roofing, gutters, and outdoor sculptures. Additionally, copper's antimicrobial properties make it useful in medical settings, where it can help prevent the spread of bacteria and viruses.

Copper is widely used in various industries, including construction, electronics, telecommunications, transportation, and renewable energy. It is also a key component in the manufacturing of electrical appliances, motors, generators, and electronic devices. Table 2.1 Shows the properties of the materials that are being used in this research.

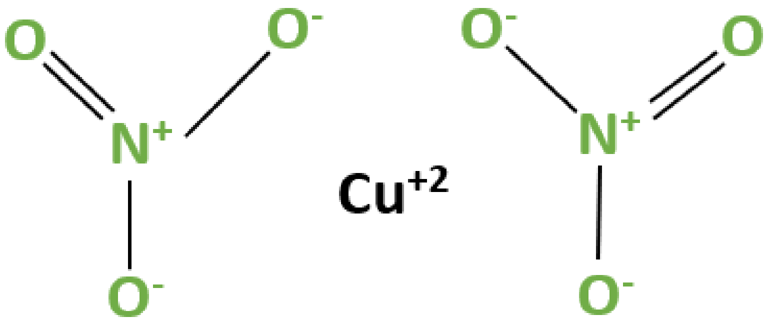


Figure 2.3: Copper Structural Formula

Table 2.1: Materials Properties

Sr. #	**Material Name**	**Linear Density**	**Melting Point (°C)**	**Tensile Strength**
1	Kevlar	1420 denier	500	3.6-4.0 GPa
2	HPPE Intermingle	200 denier	130-137	2.5-3.5 GPa
3	Copper	5.76 g/cm	`1085	200-250 GPa

2.2 Methods

Keeping material parameters constant knitted inlaid structures were developed on hand flat machine using conductive yarn as an inlaid material. Inlay braid was produced on braiding machine using copper as core while kevlar as sheath to form inlay braid. Modeling of resistance values will be done against mechanical damages against breaking resistance fabrics to induce self-diagnostic properties in knitted fabrics for successful survival in mechanical applications.

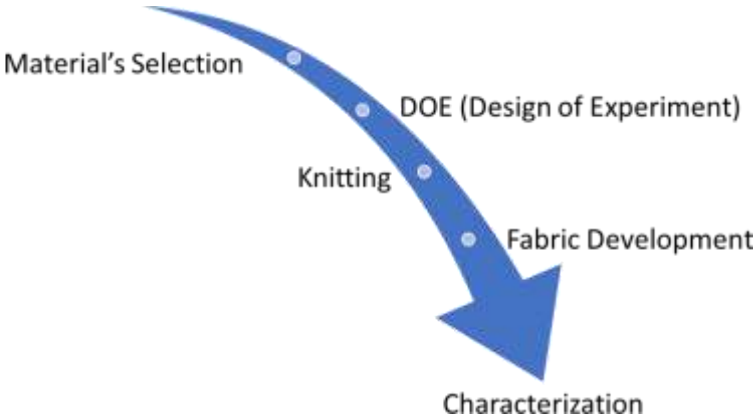


Figure 2.4: Research Methodology

2.2.1 Methodology

Following the standard operating procedures knitted fabrics samples were developed on Hand Flat V-Bed knitting machine with 7 gauge. For inlay yarns insertion special low height inlay feeders were utilized and desired repeat of inlaid yarns was obtained in the fabric. Keeping material parameters constant knitted inlaid structures were developed using conductive yarn as an inlaid material. The fabric was prepared on the hand knitting machine (Figure 2.1) with 7 gauge. Once the designs were ready, the knitting machine was set up accordingly. This included selecting the appropriate needles and yarn feeders. The yarn to be used for knitting the fabric were selected HPPE, kevlar, and copper based on the desired properties. The kevlar braid using copper winding as core was inlayed with hand and the other yarns will be fed using feeders of the machine.

Figure 2.5: Hand Flat Knitting

2.2.2 Inlay Method

The inlay yarn that was used was kevlar braid which was braided using copper in its core.This braid was inlaid manually by hand in every 2nd and 4th course of different fabric.

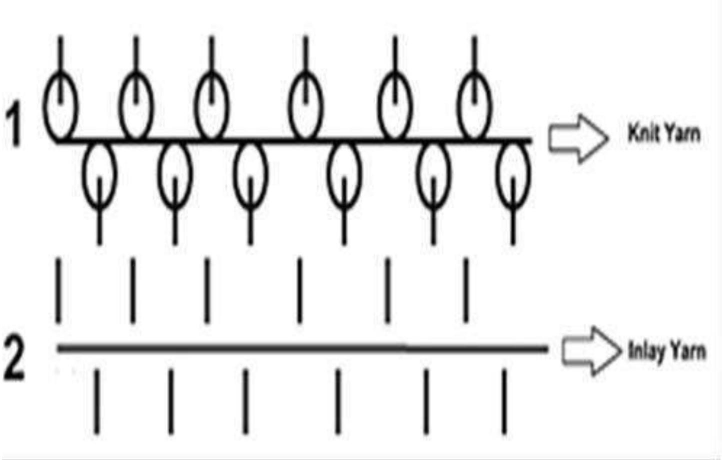


Figure 2.6: Schematic Description of Inlay Yarn in Knit Structure

2.3 Design of Experiment

The research has been carried out following the below design of experiment which is detailed in Table 2.2. Inlay yarn was developed using copper core in an Aramid braid.

Table 2.2: Design of Experiment

Sr. No.	Inlay Material	Base Material	Structure
1	Aramid braid with copper core	HPPE	1×1 Rib (2nd Course)
2	Aramid braid with copper core	HPPE	1×1 Tubular Rib (2nd Course)
3	Aramid braid with copper core	HPPE	1×1 Milano (2nd Course)
4	Aramid braid with copper core	HPPE	1×1 Rib (4th Course)
5	Aramid braid with copper core	HPPE	1×1 Tubular Rib (4th Course)
6	Aramid braid with copper core	HPPE	1×1 Milano (4th Course)

7	Aramid braid with copper core	HPPE	1×1 Rib (2nd Course) layered with S/J
8	Aramid braid with copper core	HPPE	1×1 Tubular Rib (2nd Course) layered with S/J
9	Aramid braid with copper core	HPPE	1×1 Milano (2nd Course) layered with S/J
10	Aramid braid with copper core	HPPE	1×1 Rib (4th Course) layered with S/J
11	Aramid braid with copper core	HPPE	1×1 Tubular Rib (4th Course) layered with S/J
12	Aramid braid with copper core	HPPE	1×1 Milano (4th Course) layered with S/J

2.3.1 Testing Procedure

The resistance measurement was conducted using a method that involves connecting probes with inlaid copper yarns. A reliable and efficient means of determining the resistance of a material or specimen under test is offered by this technique. By establishing a connection between the probes and the copper yarns, electrical current can flow through the material, and its resistance can be measured.

2.4 Standard Testing for Response Variables

Response variables measurement includes following standard testing methods detailed in Table 2.3:

Table 2.3: Testing Standards

Sr. No.	Characterization	Standard	Units
1	Cut Resistance	BS EN 388 (2016)	Grading
2	Tensile Testing	ISO-13934-1	Newton (N)
3	Electrical Resistance	Lab developed	kΩs
4	OMMC	AATCC 195	...

5	Stiffness	ASTM D 4032	Force (gf)
6	Air Permeability	ISO 9237	mm/sec

2.4.1 Knitted Fabric Development

Following the standard operating procedures knitted fabrics samples were developed on hand flat v-bed knitting machine. For inlay yarns insertion special low height inlay feeders were utilized and desired repeat of inlaid yarns was obtained in the fabric. The Inlay yarn was inlaid manually in the desired courses. Two yarns of high-performance polyethylene 200 denier were simultaneously passed through single guide bar and feeder to feed them together. Samples were relaxed for almost 24 hours and then these samples were carried out for testing. While the specifications of machine included four feeders, 7 gauge, 500 needles and width of 36 inches.

2.4.2 Fabric Samples

Following are the microscopic images of the materials and fabric samples.

Figure 2.7: Microscopic view of Aramid Braid with Copper Core

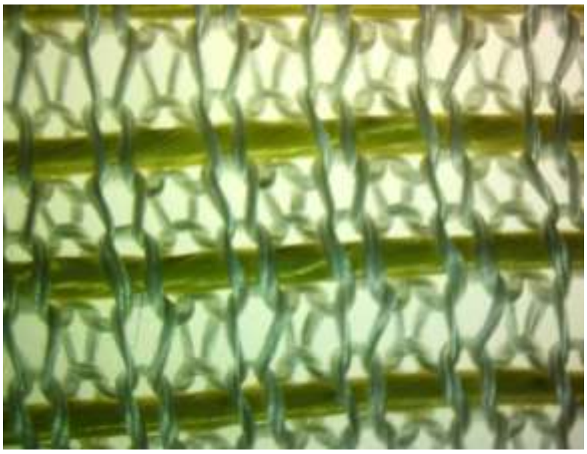


Figure 2.8: Microscopic view of Rib (2nd Course)

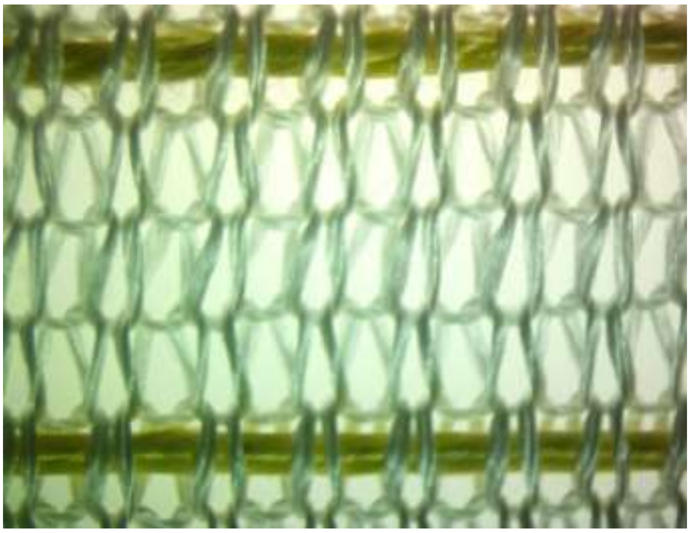


Figure 2.9: Microscopic view of Rib (4th Course)

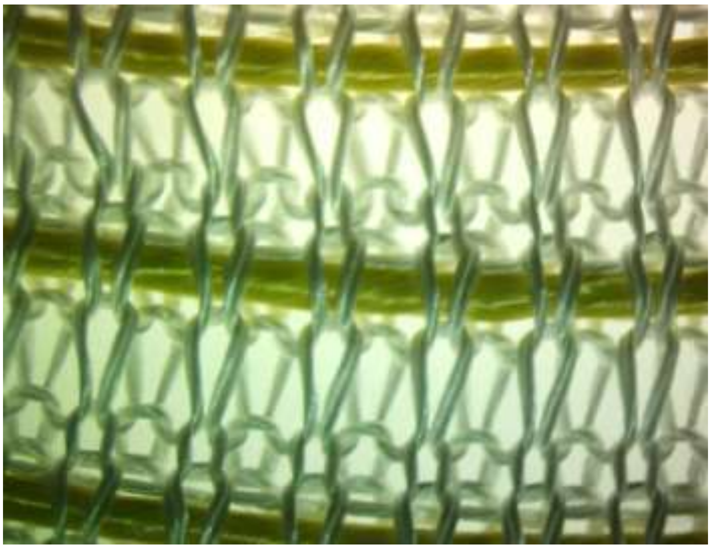


Figure 2.10: Microscopic view of Tubular Rib (2nd Course)

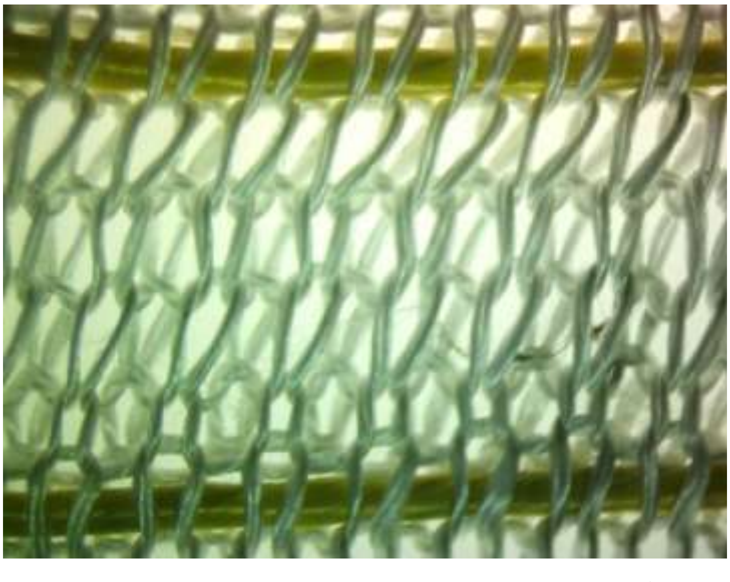


Figure 2.11: Microscopic view of Tubular Rib (4th Course)

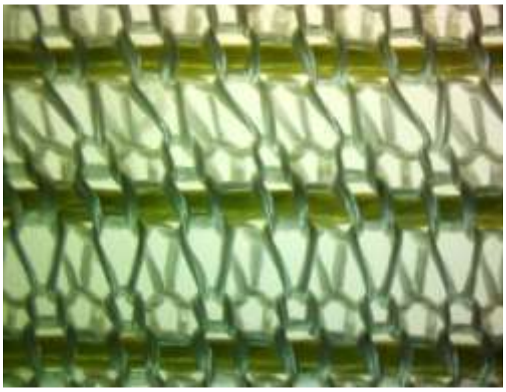


Figure 2.12: Microscopic view of Milano Rib (2nd Course) Front view

Figure 2.13: Microscopic view of Milano Rib (2nd Course) Back View

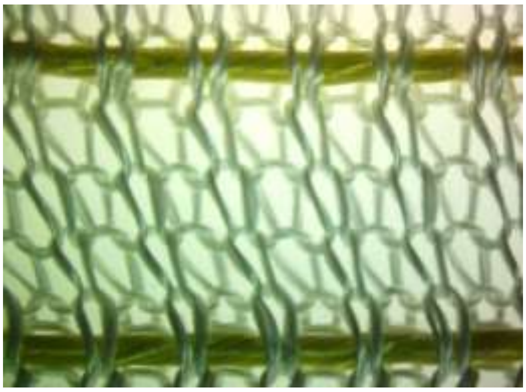


Figure 2.14: Microscopic view of Milano Rib (4th Course) Front View

Figure 2.15: Microscopic view of Milano Rib (4th Course) Back View

2.4.3 Testing Equipment

The testing equipment that is being used for the performed tests are as follows:

2.4.3.1 Universal Testing Machine

Tensile testing and was performed on UTM (Universal Testing Machine) present in NCCM laboratory of NTU [44] specimens of standard sizes were prepared while for resistance measurement electrical resistance equipment were being used. The speed of a UTM refers to the rate at which the load is applied to the specimen during testing. The force applied during tensile testing depends on the strength and nature of the material being tested.

Figure 2.16: Universal Testing Machine [45]

Specimens were clamped between both jaws of equipment and resistance values were noted while keeping change in mechanical damages until the breaking points of specimens during tensile loading. The mechanical damages w.r.t time was noted down on the computer using software and results were taken out in an excel file.

2.4.3.2 Resistance Measurement Techniques

Resistance measurement of specimens being tested required an accurate and very sensitive instrument which can detect very fine changes in the resistance of samples being tested. An instrument by manufacturers of national instruments was utilized for resistance measurement named as (NI myDAQ). The instrument was computer controlled and all required electric parameters were easily assessable, controllable, and recordable on computer screen [46].

Figure 2.17: NI myDAQ Tester [46]

2.4.3.3 Cut Resistance Measurement Techniques

The test method for cut protection has up until now been conducted via what is known as a “blade cut test”. A rotating circular knife is constantly moving to and fro with a defined force (5N) on the test object, until the blade breaks through the material [47].

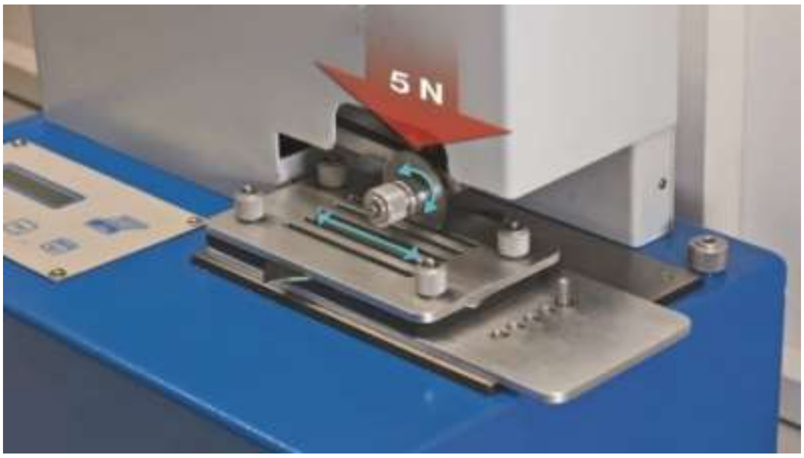


Figure 2.18: Cut Resistance Tester [47]

2.4.3.4 Moisture Management Tester

The MMT is a unique instrument that precisely measures liquid management properties of fabrics. It uses concentric rings of pins as sensors. A perspiration-like solution is applied to the upper surface of a horizontal sample, and changes in electrical resistance are measured as the solution moves through the fabric. In just two minutes, the MMT provides data on moisture management, transport capability, wetting time, absorption rate, and max wetted radius for both top and bottom surfaces of the fabric [48].

Figure 2.19: Moisture Management Tester [48]

2.4.3.5 *Stiffness Tester*

ASTM D 4032 – 92 test method for measuring fabric stiffness by the circular bend procedure. This is a method of multidirectional force action to a specified strain. Its principle of measurement consists in determining the maximal force of a mandrel causing a simultaneous multidirectional fabric strain by pushing a sample through the tester table hole. Stiffness measurements according to this method were performed by means of a digital pneumatic. This instrument plays a crucial role in quality control, research, and development processes across industries where stiffness is a critical factor, enabling manufacturers to ensure compliance with industry standards and meet customer requirements [49].

Figure 2.20: Stiffness Tester [49]

2.4.3.6 Air Permeability Measurement

The knitted samples were conditioned for 48 hours in atmospheric conditions of 20 ± 2 °C temperature and 65 ± 2% relative humidity before the tests were performed. The air permeability of the samples in mm/s was measured according to the method specified by ISO 9237, using an SDL Atlas Mozia air permeability tester. This test is crucial for assessing fabric comfort and functionality, particularly in sports and outdoor applications. It helps in the development of more breathable and comfortable textiles [50].

Figure 2.21: Air Permeability Tester [50]

Chapter 3

Results & Discussion

This chapter presents the findings and analysis of various mechanical and comfort tests conducted on the fabric. The mechanical tests, including tensile testing and cut resistance assessment, provide crucial insights into the fabric's strength and durability. Additionally, the chapter explores the fabric's comfort properties through tests such as air permeability, moisture management, and stiffness evaluation. Through a comprehensive examination of these test results, the chapter aims to elucidate the fabric's performance characteristics and its suitability for specific applications. The results of the developed samples are discussed below in this chapter.

3.1 Physical Parameters

Physical parameters of samples were measured after relaxation and are plotted in Table 3.1.

Table 3.1: Physical Parameters of Fabric Samples

Sr. #	Fabric Structure	S.L (cm)	Courses/cm (CPcm)	Wales/cm (WPcm)
1	1×1 Rib (2nd Course)	0.95	6	4
2	1×1 Rib (4th Course)	0.95	6	4
3	1×1 Tubular Rib (2nd Course)	0.95	6	4
4	1×1 Tubular Rib (4th Course)	0.95	6	4
5	1×1 Milano Rib (2nd Course)	0.95	6	4
6	1×1 Milano Rib (4th Course)	0.95	6	4

The stitch length of a knitted fabric determines the amount of yarn used in loop formation. Finer fabrics have a tighter stitch length, while coarser fabrics have a looser stitch length. In this research, a coarser gauge knitting machine was used to create reinforcements, resulting in higher stitch length values. All fabrics were made using the same machine and material parameters, ensuring consistent stitch length. The number of courses and wales per centimeter defines stitch density, which affects fabric tightness and GSM.

3.2 Mechanical Testings

To determine self-diagnostic properties samples were subject to mechanical testing e.g., tensile testing to have their responses with mechanical forces. Testing of developed specimens was done according to international standards on universal testing machine. Mechanical testing results for all tested specimens has been plotted in Table 3.3.

3.2.1 Cut Resistance Testing

The test that was being performed for measurement of cut resistance measurement was protective gloves against mechanical risks. The standard that was used BS EN 388 (2016)**.** The temperature that was provided 20.3˚C and the humidity was 26.1%. The results of the test are plotted in the below Table 3.2.

Table 3.2: Cut Resistance Testing Summary

Sr. #	Fabric Structure	Blade cut resistance index	Level of performance
1	1×1 Rib (2nd Course)	23	5
2	1×1 Rib (4th Course)	10	4
3	1×1 Tubular Rib (2nd Course)	15	4
4	1×1 Tubular Rib (4th Course)	15	4
5	1×1 Milano (2nd Course)	18	4
6	1×1 Milano (4th Course)	20	5

Remarks: Level of performance 1 is poor, whereas 5 is best.

The cut resistance testing was performed using the standard methods and the above results showing the values which indicates its level of performance against cut resistance index.

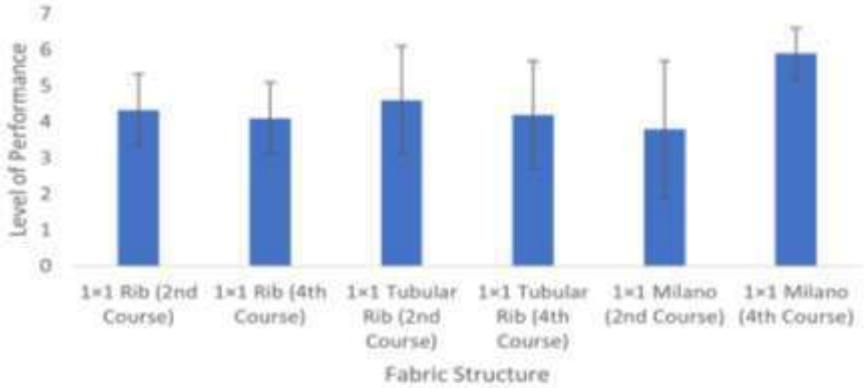


Figure 3.1: Cut Resistance Testing Variations of Different Developed Structures

The graph plotted keeping the level of performance on y-axis and fabric structure on x-axis showing the difference between them and the error bars showing the difference between the measured values.

3.2.2 Tensile Testing

The tensile testing that was performed upon these samples

3.2.2.1 1×1 Rib (2nd Course)

Aramid braid was inlayed in every 2nd course of the knitted fabric.

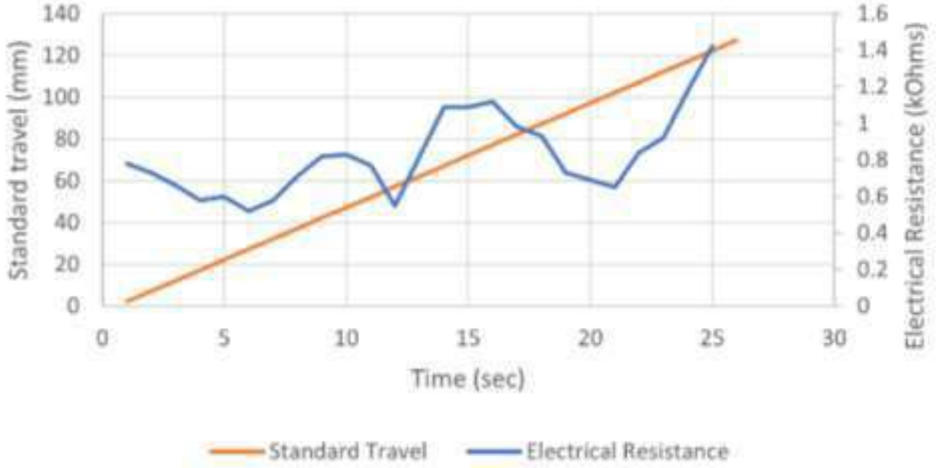


Figure 3.2: 1×1 Rib (2nd Course) Graph

The above graph exhibit that linear increase in stress strain curve is also causing almost linear increase in electrical resistance of specimen. Electrical resistance keeps (Figure 3.2). Tensile testing graph 1×1 Rib (2nd Course) increasing with as tensile force increases while after breaking point or point of mechanical damage the value of stress strain starts increasing. The phenomena occurs because at the point cracks became so much propagated in the specimen that electrical resistance could not return towards its starting values. Hence when the sample eventually breaks the electrical resistance also reaches the out of limit value. It could be observed from the graph that for each peak on stress strain curve there is also a peak on electrical resistance curve. Hence it can be said that mechanical damages lead to an increase in electrical resistance of specimen.

3.2.2.2 1×1 Rib (4th Course)

Aramid braid was inlayed in every 4th course of the knitted fabric.

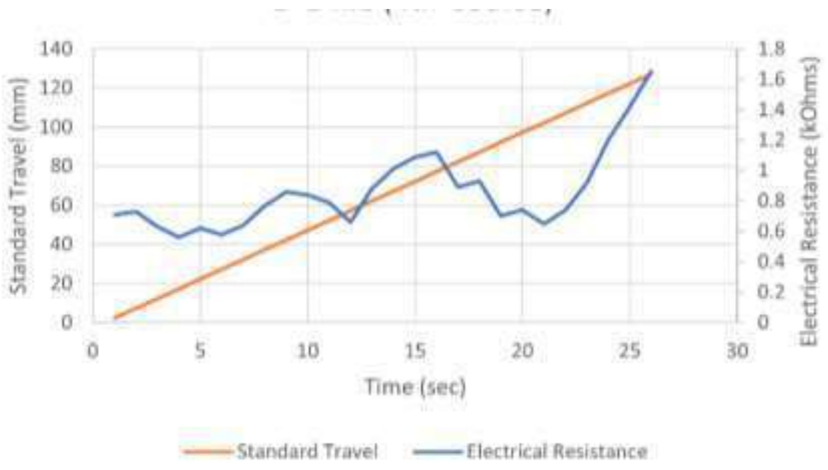


Figure 3.3: 1×1 Rib (4th Course) Graph

The above graph exhibit that linear increase in stress strain curve is also causing almost linear increase in electrical resistance of specimen. Electrical resistance keeps (Figure 3.3). Tensile testing graph 1×1 Rib (4th Course) increasing with as tensile force increases while after breaking point or point of mechanical damage the value of stress strain starts increasing. The phenomena occurs because at the point cracks became so much propagated in the specimen that electrical resistance could not return towards its starting values. Hence when the sample eventually breaks the electrical resistance also reaches the out of limit value. It could be observed from the graph that for each peak on stress strain curve there is also a peak on electrical resistance curve. Hence it can be said that mechanical damages lead to an increase in electrical resistance of specimen.

3.2.2.3 1×1 Tubular Rib (2nd Course)

Aramid braid was inlayed in every 2nd course of the knitted fabric.

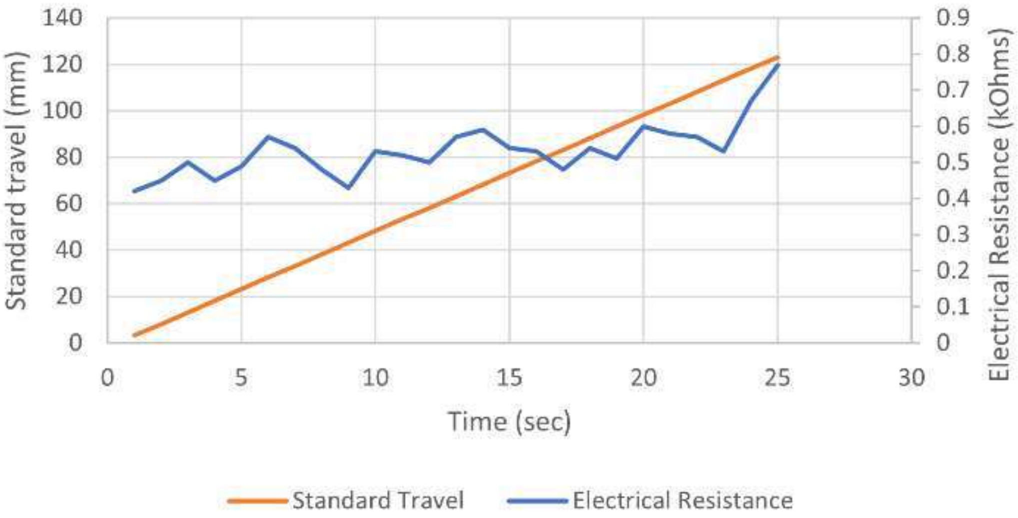


Figure 3.4: 1×1 Tubular Rib (2nd Course) Graph

The above graph exhibit that linear increase in stress strain curve is also causing almost linear increase in electrical resistance of specimen. Electrical resistance keeps **(**Figure 3.4). Tensile testing graph 1×1 tubular rib (2nd Course) increasing with as tensile force increases while after breaking point or point of mechanical damage the value of stress strain starts increasing. The phenomena occurs because at the point cracks became so much propagated in the specimen that electrical resistance could not return towards its starting values. Hence when the sample eventually breaks the electrical resistance also reaches the out of limit value. It could be observed from the graph that for each peak on stress strain curve there is also a peak on electrical resistance curve. Hence it can be said that mechanical damages lead to an increase in electrical resistance of specimen.

3.2.2.4 1×1 Tubular Rib (4th Course)

Aramid braid was inlayed in every 4th course of the knitted fabric.

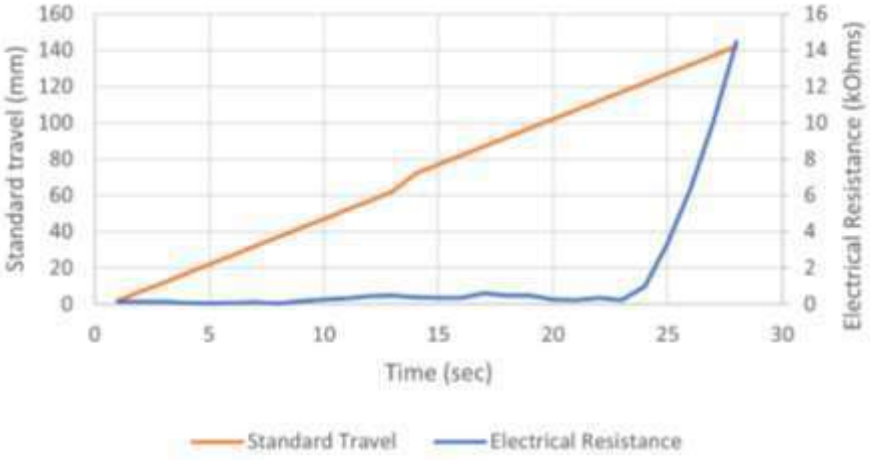


Figure 3.5: 1×1 Tubular Rib (4th Course) Graph

The above graph exhibit that linear increase in stress strain curve is also causing almost linear increase in electrical resistance of specimen. Electrical resistance keeps (Figure 3.5). Tensile testing graph 1×1 tubular rib (4th Course) increasing with as tensile force increases while after breaking point or point of mechanical damage the value of stress strain starts increasing. The phenomena occurs because at the point cracks became so much propagated in the specimen that electrical resistance could not return towards its starting values. Hence when the sample eventually breaks the electrical resistance also reaches the out of limit value. It could be observed from the graph that for each peak on stress strain curve there is also a peak on electrical resistance curve. Hence it can be said that mechanical damages lead to an increase in electrical resistance of specimen.

3.2.2.5 1×1 Milano Rib (2nd Course)

Aramid braid was inlayed in every 2nd course of the knitted fabric.

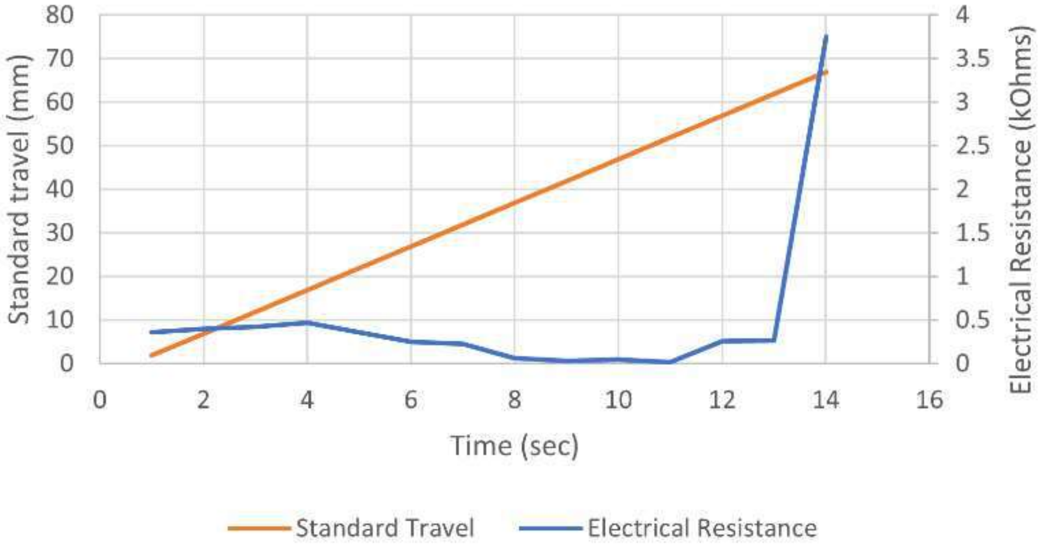


Figure 3.6: 1×1 Milano Rib (2nd Course) Graph

The above graph exhibit that linear increase in stress strain curve is also causing almost linear increase in electrical resistance of specimen. Electrical resistance keeps (Figure 3.6). Tensile testing graph 1×1 milano rib (2nd course) increasing with as tensile force increases while after breaking point or point of mechanical damage the value of stress strain starts increasing. The phenomena occurs because at the point cracks became so much propagated in the specimen that electrical resistance could not return towards its starting values. Hence when the sample eventually breaks the electrical resistance also reaches the out of limit value.

Hence it can be said that mechanical damages lead to an increase in electrical resistance of specimen.

3.2.2.6 1×1 Milano Rib (4th Course)

Aramid braid was inlayed in every 4th course of the knitted fabric.

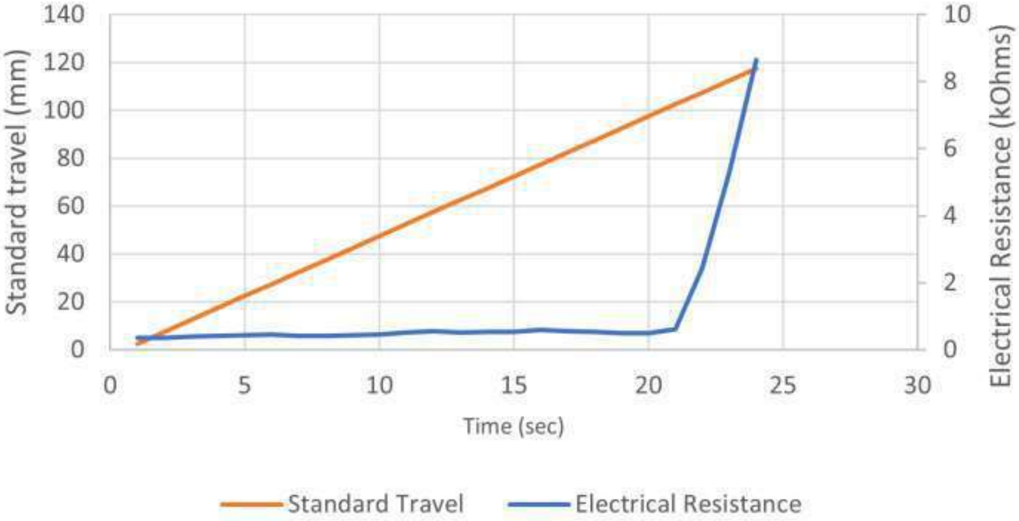


Figure 3.7: 1×1 Milano Rib (4th Course) Graph

The above graph exhibit that linear increase in stress strain curve is also causing almost linearincrease in electrical resistance of specimen. Electrical resistance keeps (Figure 3.7).

Tensile testing graph 1×1 milano Rib (4th Course) increasing with as tensile force increases whileafter breaking point or point of mechanical damage the value of stress strain starts increasing.

The phenomena occurs because at the point cracks became so much propagated in the specimen that electrical resistance could not return towards its starting values. Hence when the sample eventually breaks the electrical resistance also reaches the out of limit value. It could be observed from the graph that for each peak on stress strain curve there is also a peakon electrical resistance curve.

Hence it can be said that mechanical damages lead to an increase in electrical resistance of specimen.

3.2.3 Comfort Testing Summary

The results for comfort testing of the developed samples are mentioned below in the Table 3.3.

Table 3.3: Comfort Testing Summary of Results

Sr. #	**Sample Name**	**Air Permeability**		**(OMMC)**	**Stiffness Force (gf)**
		Face	**Back**		
1	1×1 Rib (2nd Course)	2793	2757	0.52	165
2	1×1 Tubular Rib (2nd Course)	2647	2590	0.48	170
3	1×1 Milano (2nd Course)	2233	2186	0.45	190
4	1×1 Rib (4th Course)	2460	2273	0.45	165
5	1×1 Tubular Rib (4th Course)	3370	3350	0.42	200
6	1×1 Milano (4th Course)	2861	2976	0.45	145
7	1×1 Rib (2nd Course) layered with S/J	872	809	0.00	665
8	1×1 Tubular Rib (2nd Course) layered with S/J	795	696	0.00	670
9	1×1 Milano (2nd Course) layered with S/J	711	619	0.00	740
10	1×1 Rib (4th Course) layered with S/J	751	733	0.00	735
11	1×1 Tubular Rib (4th Course) layered with S/J	847	743	0.00	640
12	1×1 Milano (4th Course) layered with S/J	916	841	0.00	680

The comfort testing summary of the above-mentioned samples in Table 3.3 is as follow:

The samples 5 and 12 (1×1 tubular rib and 1×1 milano, respectively, in the 4th course) have the highest air permeability values. This indicates that these fabrics allow more air to pass through, making them more breathable compared to the other samples. Samples 7-12, which are layered with S/J, show significantly reduced air permeability, with values close to zero. The addition of the S/J layer acts as a barrier, restricting the airflow and making the fabrics less breathable. Samples 6, 9, and 12 (1×1 milano in different courses) have relatively lower stiffness force values. This suggests that these fabrics are softer and more flexible compared to the other samples. The layered samples (7-12) exhibit slightly increased stiffness force values compared to their non-layered counterparts. The addition of the S/J layer contributes to a slight increase in stiffness. The different fabric structures (1×1 rib, 1×1 tubular rib, and 1×1 milano) can influence air permeability and stiffness force. Variations in fabric structure and knitting pattern can result in different arrangements of yarns, affecting the airflow and flexibility of the fabric. The addition of S/J (likely referring to a specific material or treatment) in the layered samples creates a barrier that significantly reduces air permeability and slightly increases stiffness force.

Chapter 4

Conclusions

In this chapter, we will discuss the conclusion of the research being done and the future work that can be carried out. The results reveal that all the fabric samples made from kevlar, copper and HPPE (High Performance Polyethylene) which shows self-diagnostic fabrics could detect any sort of changes occurring in them e.g., mechanical, and electrical. Self-Diagnostic fabrics developed using conductive knitted fabrics are worthwhile for structural health monitoring. The developed weft knitted inlaid fabric for protective applications focused on cut resistance has yielded successful results. The results of the developed fabrics showed different changes in their performance. In comparison with the fabric having yarn inlayed in every 4th course, the knitted samples having inlayed yarn in every 2nd course showed better change in electrical resistance. The rib samples with 2nd course inlay yarn showed better cut resistance properties than the 4th course inlay rib structure because of its loose structure also it has more inlay yarn encounters the cutter in testing. The tubular structures with 2nd and 4th course inlayed yarn have the same performance in cut testing. Overall, in cut testing engineered fabric showed 86% resistance to cutting. The rib 1×1 with every 2nd course inlayed yarn sample showed better air permeability as compared to other tubular and milano samples. In comfort testing the samples showed best air permeability and keeping its values as reference we can see that the tubular 1×1 and milano 1×1 with 2nd course inlay yarn shows 5.22% and 20.5% respectively, difference in values relative to rib 1×1 structure. For 4th course inlayed structures, the air permeability values of fabric showing aapproximately 37.04% for the tubular rib and 16.30% for the milano. Air permeability decreases with an increase in area density of samples; therefore, there is a good relation between area density and air permeability for all the kinds of knits examined. The OMMC values for the developed samples have 7.69% for tubular rib and 13.46% for milano rib relative to rib structures. It is observed that the increase in the fabric tightness decreases the air permeability and increases the wicking ability. It is determined that fabric tightness also has different effects on different knitting types in terms of moisture management properties. The stiffness of the fabric samples relative to rib structures with inlay in 2nd course shows approximately 3.03% for the tubular rib and 15.15% for the milano. Bending properties such as average bending rigidity and hysteresis of weft knits increased with knit density. The engineered fabric demonstrated exceptional cut resistance, incorporated self-diagnostic functions for enhanced safety, and prioritized comfort parameters for improved wearability.

4.1 Future work

The research presents the simplest model of knitted reinforced fabric having self-diagnostic properties. But the described relationship of electrical resistance and mechanical changes of fabric could be utilized for more advanced fabric manufacturing e.g., conductive yarns could be used which will serve more precisely for structural health monitoring, terminals could be connected via more precise method for better analysis of electrical resistance etc. In a nutshell, the research opens a pathway for inducing self-diagnostic properties in knitted reinforced fabric which may have much more destinations in future to work.

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