



CHAPTER 2
LITERATURE REVIEW



CHAPTER 2
LITERATURE REVIEW

2.0 Introduction

Textiles date back to several thousand years, is one of the primary needs of humans. But looking at the technical textiles as we perceive them today, they are quite young and have seen tremendous growth in the application of fibrous materials in non-conventional sectors in the last 2 to 3 decades. These are things like protective clothing, medical products like medical textiles, automotive components, geotextiles, building materials, sports, and many other areas. As the textile materials used in these areas are for specific technical purposes, that is why they are termed “technical textiles” [1]. The technical textiles are designed to perform heavy-duty and demanding applications through the use of high-performance fibres, yarns, and, chemicals that are required to meet the specific performance. Special methods and specially built machines are also required to manufacture technical textiles.

Technical textiles are value-added textile products that provide added functionality and applications other than the regular textile supply chain. So, technical textiles are defined as textile materials and products manufactured primarily for their functional properties rather than their aesthetic and decorative characteristics. Technical textiles are classified into 12 main areas of application, like Agrotech (agro-textiles), Buildtech (construction textiles), Clothtech (clothing textiles), Geotech (geo-textiles), Hometech (domestic textiles), Indutech (industrial textiles), Meditech/Medtex (medical textiles), Mobiltech (textiles used in transport), Oekotech or echotech (environmentally friendly textiles), Packtech (packaging textiles), Protech (protective textiles), and Sporttech (sports textiles). Whereas Buildtech is related to building and construction, like fibre-reinforced concrete, this technical textile will also come under buildtech or composites [2-3].

Generally, steel has been used for centuries in the building and construction industry, but technical textiles could make their way to replace conventional materials due to various advantages [4]. The main advantages of technical textiles over conventional

products like steel or wood are their flexibility, elasticity, strength, and design possibilities. They are mainly used for their lightweight nature and are stronger than steel as far as specific strength is concerned [5-6]. These features make these textile-based composite materials to be used in automotive, aerospace, civil, and mechanical engineering applications.

In the area of composite materials, various reinforcement and matrix materials are employed to enhance performance characteristics. Common reinforcement materials include high-performance fibers such as polyester, polypropylene, nylon, carbon, glass, aramid, and basalt, each offering unique properties like high tensile strength, thermal stability, and resistance to corrosion. The matrix materials typically used are polymers (both thermosetting and thermoplastic resins), metals, and ceramics, which provide the composites with shape and protect the fibers from environmental and mechanical damage.

Research in this field adopts several approaches to optimize the properties and applications of these materials. Experimental studies focus on understanding the mechanical behavior, durability, and failure mechanisms of composites under different loading conditions and environments have been reviewed. This literature survey will provide an in-depth review of these research approaches, exploring the latest advancements and identifying gaps in the current knowledge. It will cover the various reinforcement and matrix materials being used, their respective benefits and limitations, and the methodologies employed to enhance their performance. By doing so, it aims to lay the groundwork for further research into optimizing braided structures for structural applications, ultimately contributing to the broader adoption of these innovative materials in the construction and engineering industries.

2.1 Concepts of Braiding

Textile braiding is the process of interlacing three or more strands of yarn, thread, or other materials to form a woven-like intertwined structure [7]. Braiding can be done by hand or by machine and is used to create a variety of textile products, including ropes, cords, straps, and trimmings. Braids can be created using a variety of techniques, including flat braid, round braid, and square braid. These techniques involve different patterns of over-under weaving and can be adjusted to create braids of different thicknesses and textures. In addition to its functional uses, textile braiding can also be

used for decorative purposes. Braided trims and edgings can be added to clothing, home decor items, and accessories to add visual interest and texture.

Braids are characterized depending on yarn interweaving, fibre/yarn orientation, fabric shape, and purpose. Regular braids are $2/2$ patterns of yarn intertwined, as seen in Figure 2.1a, the braided structure is identical to the $2/2$ twill woven fabric. The $1/1$ intertwining of yarns during braiding creates the diamond braided structure shown in Figure 2.1b, which is identical to the structure of plain woven cloth. Basket braids are $2/2$ braided structures similar to box weaves, with two yarns crossing over and beneath one another, as seen in Figure 2.1c. In contrast, Hercules braids are $3/3$ intertwining of threads during braiding, as seen in Figure 2.1d, which is identical to the $3/3$ twill weave fabric structure [8].

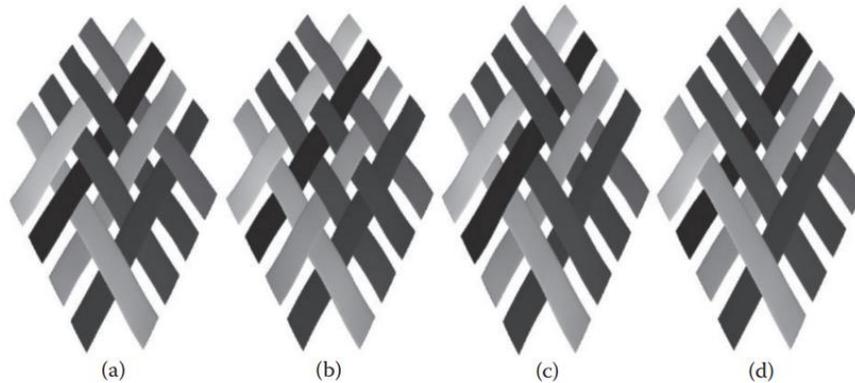


Figure 2.1 Braided structures (a) regular, (b) diamond (c) basket, and (d) Hercules braids.

2.1.1 Braiding Techniques

The braiding technique, can be classified based on various methods such as yarn intertwining, the orientation of fibres/yarns in the braided structure, the shape of the braided fabric, and the purpose of its use, as detailed here:

2.1.1.1 Bi-axial and tri-axial braid structures

Depending on the direction and arrangement of input yarns during interweaving, braided constructions are classified as bi-axial or tri-axial structures. Braiding typically produces bi-axial structures, in which two sets of yarns travel in opposite directions and are inter-twined at an angle. The incorporation of in-laid yarns along the machine direction or at the cross direction during braiding results in tri-axial structures, as seen in Figure 2.2 [9-10].

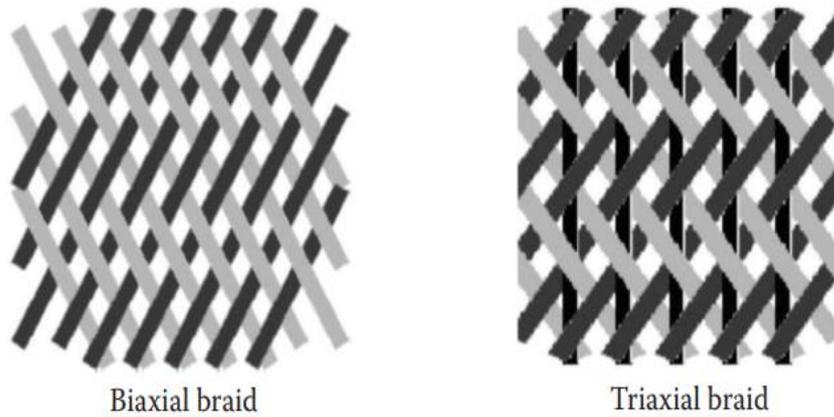


Figure 2.2 Braiding Structure

2.1.1.2 Tubular, flat, square, and solid braids

Tubular braids are manufactured on circular braiding machines and are made up of two sets of yarns in the axial direction of the braided structure, with the first set rotating continuously in a clockwise direction and intertwining with the second set, which spirals anticlockwise. The anticlockwise and clockwise methods cause the sets of yarns to cross each other in a full circular path, with each set of yarns traveling at the same time, constructing a tubular structure. Yarns traveling anticlockwise or clockwise will never connect with those moving sequentially in the same direction. Tubular braiding creates braids with rotational symmetry (Figure 2.3a) [9].

Flat braids are braided structures that are shaped like ribbons, as the name implies. Flat braids, unlike tubular braids, have clockwise and anticlockwise intertwining sets of yarns that reverse at the edges and flow back in the opposite direction, resulting in a selvage braided structure, as seen in Figure 2.3b [11].

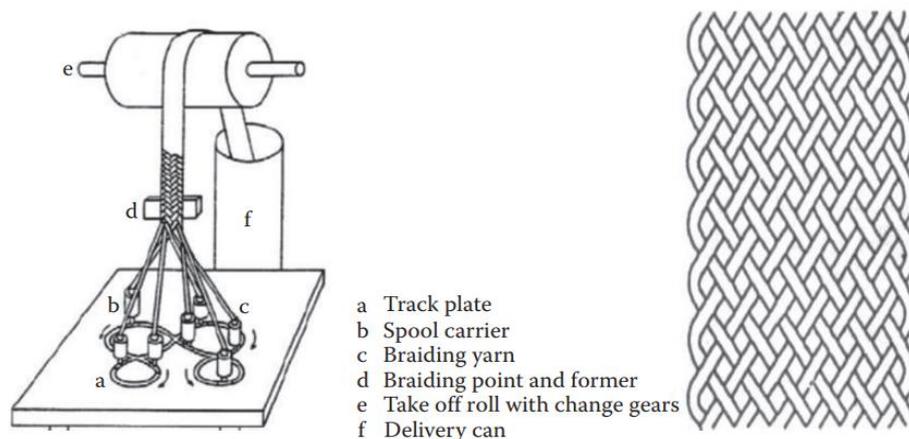


Figure 2.3 Flat braiding (a) Flat braiding machine, (b) Flat braiding structure

The square braid is a variation on the tubular braid in which yarn groups travel clockwise and anticlockwise while interlacing with yarns from the opposing group to retain a hollow center. The square shape is achieved by aligning the braid yarns with the machinery's horn gears, as illustrated in Figure 2.4 [11].

Solid braids are composed of multiple interwoven braided layers. Selective interlocking of braided layers can be performed by controlling the movement of carrier yarns during braiding, resulting in complex 3D shapes. Figure 2.4 depicts the most frequent solid braided structures, which include two-diagonal, three-diagonal, four-diagonal, spiral, and round braided structures [12].

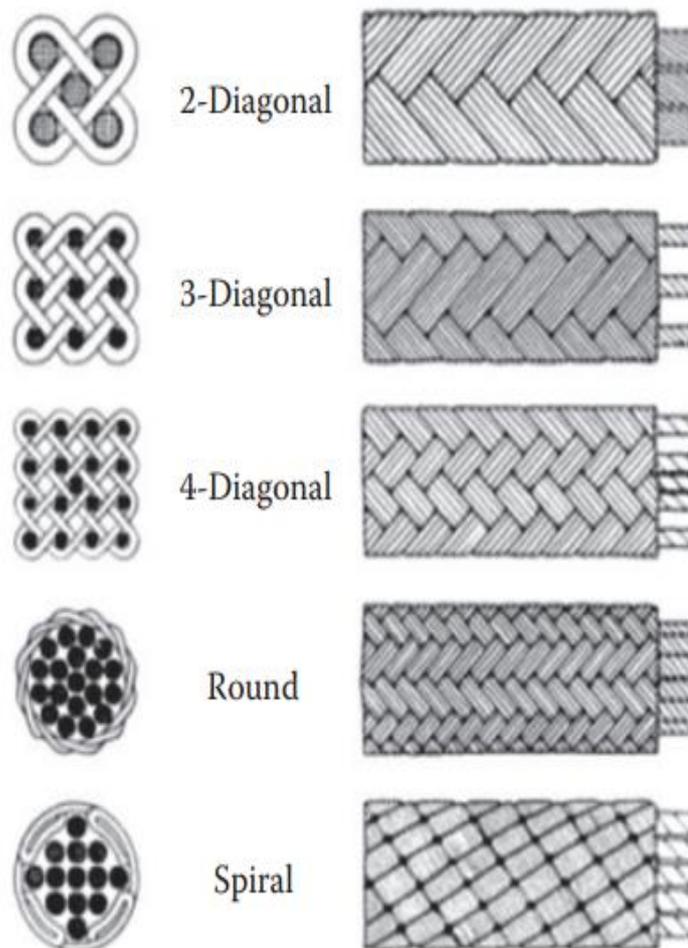


Figure 2.4 Solid braided structures

Fancy braids are braided structures that are unusually shaped or do not have a flat or tube design. Fancy braids are used as clothing decorations, trims, and fashion embellishments. Fancy braids come in many structures, colors, and interlacement kinds.

Figure 2.5, illustrates common fancy braids, including argyle (Figure 2.5a) with overlapping diamonds, pinstripe (Figure 2.5b) with thin stripes along the axis, and horizontal zigzag (Figure 2.5c) with horizontal stripes [13].



(a) (b) (c)

Figure 2.5 Fancy braided structures

2.1.2 Characteristics of Braided Structures

The characteristics of a braided structure can have a significant impact on the properties of a braided composite material. Some important characteristics of braided structures include:

1. **Braid angle:** The braid angle is the angle between the fibre bundles and the longitudinal axis of the structure (Figure 2.6). The braid angle can affect the mechanical properties of the composite, such as its stiffness, strength, and shear resistance. Lower braid angles can lead to higher stiffness and strength, while higher braid angles can increase flexibility and deformation capability [14-15].

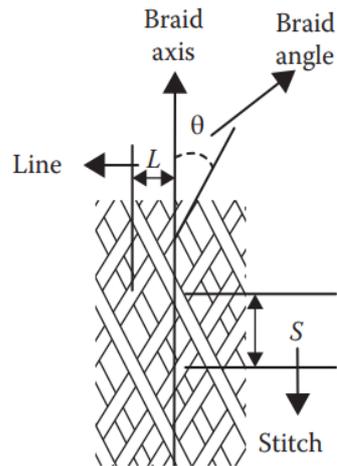


Figure 2.6 Measurement of braid angle

2. **Number of fibre bundles:** The number of fibre bundles in a braided structure can affect the mechanical properties of the composite. Higher numbers of fibre bundles can increase the strength and stiffness of the composite while also increasing its weight [12], [15].
3. **Fibre orientation:** The orientation of the fibres within the braided structure can affect the mechanical properties of the composite in different directions. Unidirectional braids, for example, provide high strength and stiffness in the longitudinal direction, while bi-directional or multi-directional braids can provide strength and stiffness in multiple directions.
4. **Density:** The density of the braided structure can affect the mechanical properties of the composite, such as its weight, stiffness, and strength. Higher densities can lead to higher stiffness and strength, but they also increase the weight of the composite [12].
5. **Porosity:** The porosity of the braided structure can affect the resin infusion process and the overall properties of the composite. Higher porosity can lead to better resin infusion and reduced weight, but it can also decrease the strength and stiffness of the composite.

The characteristics of a braided structure can be tailored to meet the specific requirements of a particular application, such as weight, stiffness, strength, and durability. By adjusting the braid angle, number of fibre bundles, fibre orientation,

density, and porosity, designers can create braided composite materials with a wide range of properties and performance characteristics [12], [16], [17].

2.2 Textile Composites

Textile composites are materials made by combining textiles, such as fibres, fabrics, and yarns, with a matrix material. The resulting composite material combines the desirable properties of both the textile and the matrix material, creating a material that is stronger, more durable, and more versatile than either material alone.

Textile composites are used in a variety of applications, such as aerospace, automotive, and sporting goods. In aerospace, for example, textile composites are used to make lightweight and strong components for aircraft, such as wings and fuselages. In the automotive industry, textile composites are used to make parts such as bumpers and body panels, which are lightweight and can help improve fuel efficiency. In sporting goods, textile composites are used to make lightweight and durable components such as tennis rackets and bicycle frames.

The properties of textile composites can be tailored to meet the requirements of specific applications by adjusting the type and arrangement of the textile reinforcement, as well as the type and amount of matrix material [18–20]. The use of advanced manufacturing techniques, such as 3D printing and automated fibre placement, has also expanded the range of possibilities for textile composites, allowing for more complex and customized designs [28].

2.2.1 Different Types of Textile Composites

A textile composite is typically made up of a reinforcing textile material (carbon, glass, etc.) in the shape of a unidirectional fabric that has been impregnated with a resin matrix to a specified and controlled degree. This operation is carried out utilizing several liquid molding techniques, including resin transfer molding (RTM), injection molding, and so on. Depending upon the formation techniques of fibre / yarn / fabric, textile composites can be divided into four categories: woven, braided, knitted, and nonwoven fabric, as shown in Figure 2.7 [21–23].

There are several different types of textile composites, each of which is distinguished by the type of textile reinforcement and the matrix material used. Some of the most common types of textile composites include:

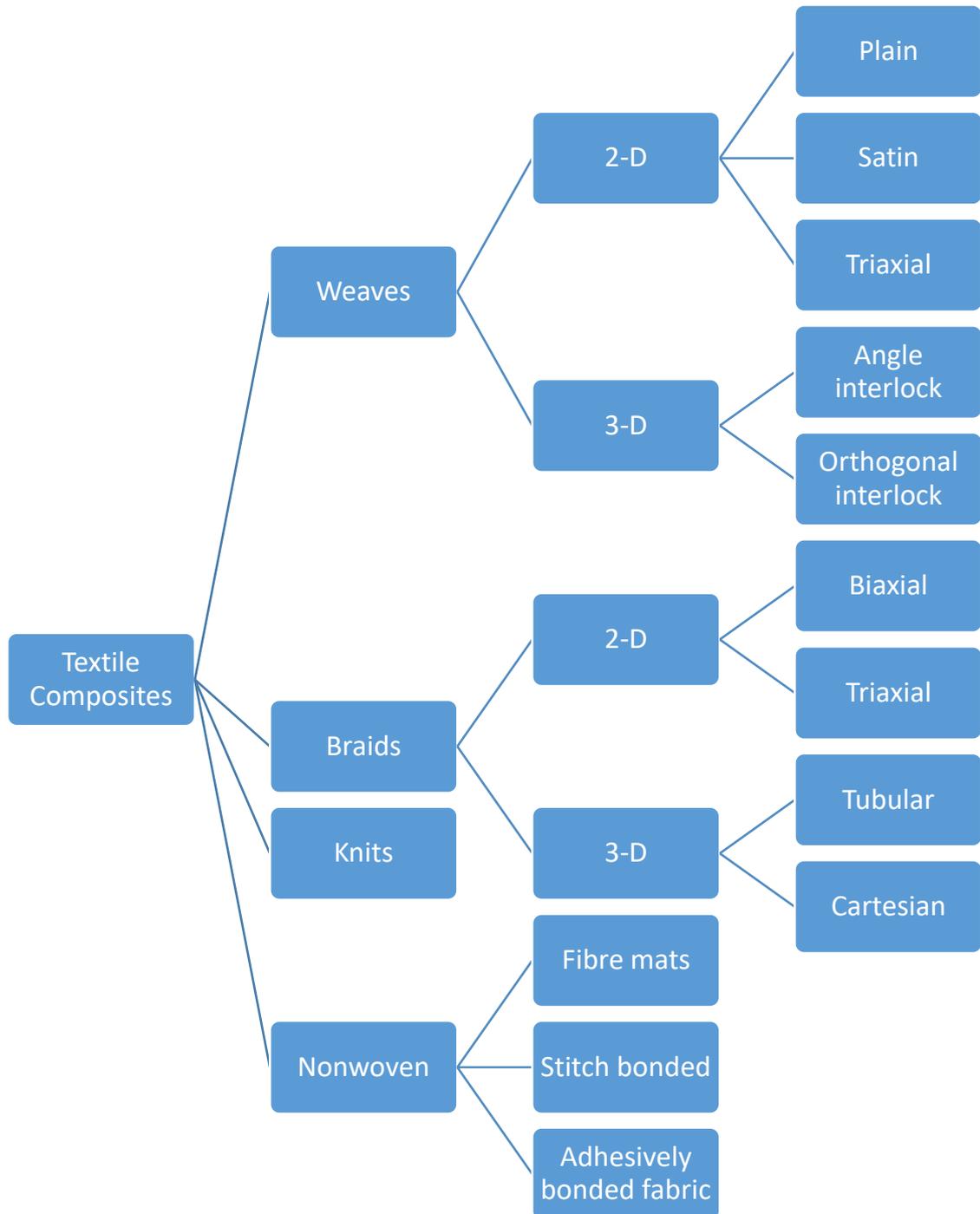


Figure 2.7 Classification of textile composites

2.2.1.1 Fibre-reinforced composites

These composites use continuous fibres, such as carbon or glass fibres, as the reinforcement material. The fibres are embedded in a matrix material, which can be a

polymer, ceramic, or metal (Figure 2.8). Fibre-reinforced composites are known for their high strength-to-weight ratio, making them ideal for use in aerospace and other industries where weight reduction is critical [24].

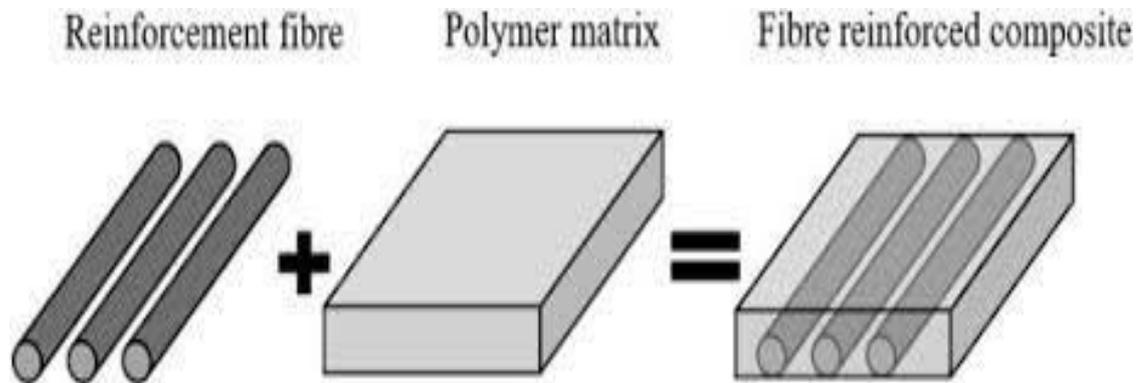


Figure 2.8 Fibre reinforced composite

2.2.1.2 Fabric-reinforced composites

These composites use woven or knitted fabrics as the reinforcement material. The fabrics are typically made from fibres such as carbon, glass, or aramid. The fabric is impregnated with a matrix material, such as epoxy or polyester resin, which fills the voids between the fibres and provides support (Figure 2.9). Fabric-reinforced composites are commonly used in the automotive and construction industries [25].

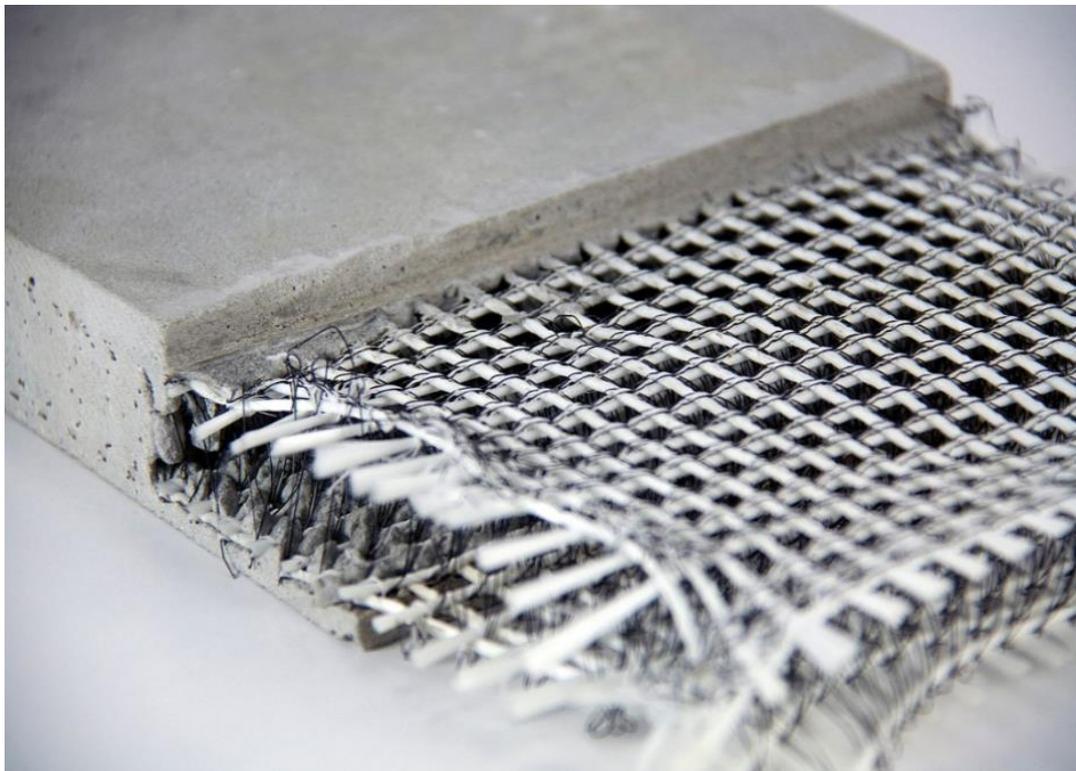


Figure 2.9 Fabric reinforced composite

2.2.1.3 Hybrid composites

These composites use a combination of different types of fibres and fabrics as reinforcement materials. For example, a hybrid composite may use both carbon and glass fibres, and a combination of woven and non-woven fabrics. Hybrid composites can be tailored to meet specific requirements, such as improved stiffness or impact resistance (Figure 2.10) [26].

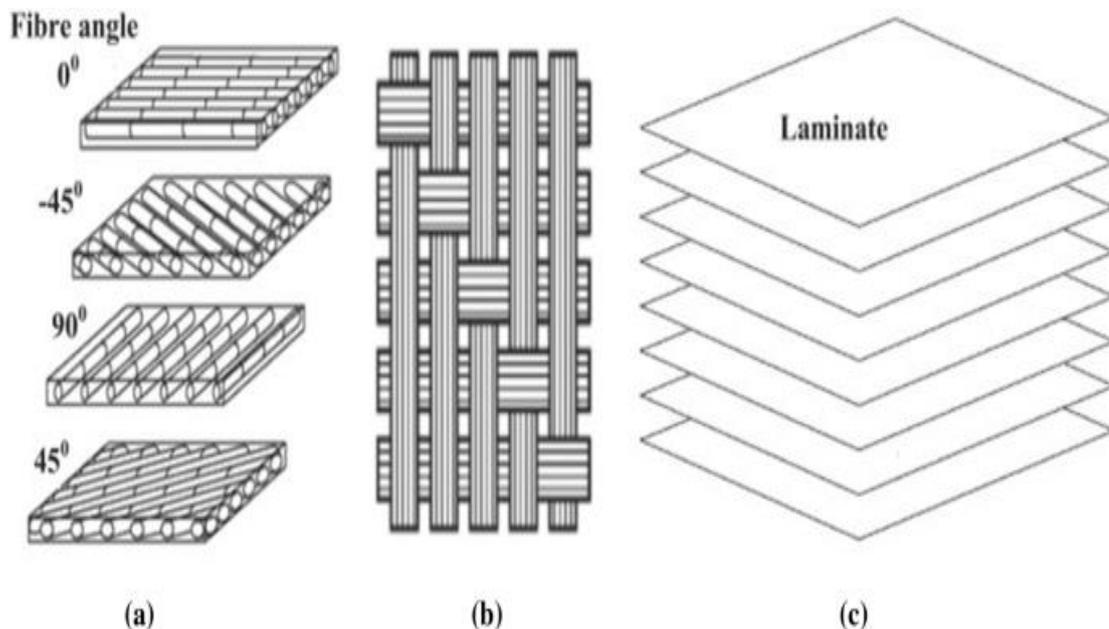


Figure 2.10 Hybrid Composite

2.2.1.4 Sandwich composites

These composites consist of a core material, such as foam or honeycomb, sandwiched between two layers of fibre-reinforced or fabric-reinforced composite materials. Sandwich composites are known for their high strength and stiffness, as well as their ability to withstand impact and vibration [27].

2.2.2 Characteristics of Textile Composites

Textile composites are composite materials made by combining fibres, yarns, or fabrics with a matrix material, such as a polymer resin. The textile reinforcement provides strength and stiffness to the composite, while the matrix material binds the fibres together and protects them from external damage. Some important characteristics of textile composites include [21], [28-32].

1. **Strength:** Textile composites can have high strength-to-weight ratios, making them strong and lightweight. The strength of a textile composite depends on the strength of the fibres or yarns used as reinforcement and the type of matrix material used.

2. **Stiffness:** Textile composites can also have high stiffness, which makes them suitable for applications that require structural integrity, such as aerospace components or automotive parts. The stiffness of a textile composite depends on the type of reinforcement, fibre orientation, and matrix material used.
3. **Durability:** Textile composites are often used in applications where durability is critical, such as in wind turbines or sporting goods. The durability of a textile composite depends on the type of reinforcement and matrix material used, as well as the manufacturing process.
4. **Fatigue resistance:** Textile composites can also have good fatigue resistance, which is important in applications that involve cyclic loading, such as aircraft structures or sports equipment. The fatigue resistance of a textile composite depends on the type of reinforcement and matrix material used, as well as the manufacturing process.
5. **Impact resistance:** Textile composites can also have good impact resistance, which makes them suitable for applications that involve high-velocity impacts, such as automotive crash structures or ballistic armor. The impact resistance of a textile composite depends on the type of reinforcement and matrix material used, as well as the manufacturing process.
6. **Customization:** Textile composites offer a high degree of customization, as the type of reinforcement, fibre orientation, and matrix material can be tailored to meet specific requirements for a given application.

2.2.3 Reinforcement Material

Textile reinforcement involves the use of textile materials to enhance the mechanical properties of composite materials. These reinforcements provide strength, stiffness, and durability to composites, making them suitable for a wide range of applications [28], [33-34]. Textile reinforcements can be made from various fibres and can take different forms, such as woven fabrics, non-woven fabrics, knitted fabrics, and braided structures.

2.2.3.1 Nylon fibre and its properties

Nylon is the generic name for a family of synthetic polymers called polyamides. Unlike natural fibres like cotton or wool, nylon is entirely man-made and derived from petroleum products.

Key characteristics:

- **Strength and durability:** One of the strongest textile fibres, nylon is resistant to abrasion. This makes it ideal for industrial applications where durability is crucial, such as in conveyor belts, ropes, and heavy-duty fabrics.
- **Lightweight:** Despite its strength, nylon is surprisingly lightweight, making it easy to handle and install in industrial settings, such as in automotive components and machinery parts.
- **Elasticity:** Nylon's elasticity allows it to absorb shocks and return to its original shape, which is beneficial in applications like vibration dampening mounts, bushings, and flexible hoses.
- **Fast drying:** Nylon does not retain moisture, which is advantageous for applications in environments where exposure to water or humidity is common, such as in marine ropes and fishing nets.
- **Chemical resistance:** Nylon resists many chemicals and oils, making it suitable for use in industrial uniforms, filters, and other applications where exposure to harsh substances is a concern. This property is also useful in manufacturing gaskets, seals, and components exposed to various chemicals[20], [35], [36].

Some downsides to consider:

- **Low moisture absorbency:** While nylon's fast-drying nature is beneficial in many applications, it can also be a drawback in situations where moisture absorption is desired, such as in certain filtration or absorbent materials.
- **Static and pilling:** Nylon can generate static electricity, which might be an issue in environments where static discharge needs to be minimized. Additionally, pilling can reduce the lifespan and effectiveness of nylon components.
- **Sun Sensitivity:** Prolonged exposure to sunlight can degrade nylon fibres, reducing their strength and elasticity. This limitation must be considered in applications exposed to direct sunlight for extended periods, such as outdoor equipment and components.

2.2.3.2 Polypropylene fibre & its properties

Polypropylene (PP) is a man-made fibre derived from a thermoplastic polymer. Widely recognized for its use in packaging, containers, and various household items, polypropylene also has significant applications in industrial textiles. Next to

polyethylene, polypropylene is the second-most produced plastic globally [12], [25], [28], [37], [38].

Important characteristics:

- **Lightweight:** Polypropylene is one of the lightest textile fibres, making it easy to handle and transport. This characteristic is beneficial in applications such as geotextiles, automotive components, and industrial packaging materials.
- **Hydrophobic (Water-repellent):** Polypropylene repels water, which is advantageous for industrial uses where moisture resistance is critical, such as in outdoor furniture, protective covers, and agricultural textiles.
- **Fast drying:** Due to its water-repellent nature, polypropylene fabrics dry quickly. This feature is useful in industrial settings where materials frequently get wet, such as in marine environments or filtration systems.
- **Durable:** Polypropylene is strong and resistant to abrasion, tears, and chemicals, making it suitable for heavy-duty applications like industrial carpets, ropes, and storage containers.
- **Low heat conductivity:** Polypropylene's ability to trap warm air efficiently makes it an excellent insulator. This property is beneficial for applications such as thermal insulation in construction and cold storage facilities.
- **Colourfast:** The dyes used in polypropylene are incorporated during manufacturing, resulting in excellent colour retention and fade resistance. This is useful for outdoor applications, signage, and industrial fabrics that require long-lasting colours [46-48].

Some downsides to consider:

- **Low breathability:** While polypropylene wicks moisture away, it doesn't allow much airflow, which can be a drawback in applications where ventilation is necessary, such as certain types of protective clothing or coverings.
- **Odour retention:** Polypropylene's inability to absorb moisture can lead to odour retention. This can be an issue in applications where hygiene and freshness are critical, such as in food packaging or medical textiles.
- **Low melting point:** Polypropylene has a lower melting point compared to other fibres. This characteristic must be taken into account during processes involving

heat, such as thermal bonding or exposure to high temperatures in industrial environments [46-48].

2.2.3.3 Polyester fibre & its properties

Polyester, scientifically known as polyethylene terephthalate (PET), is a synthetic fibre derived from petroleum, air, water, and coal. It is transformed into long, thin fibres through a chemical process, making it a highly popular textile fibre used in various industrial applications [12], [37].

Key characteristics:

- **Durable and strong:** Polyester is known for its resilience and strength. It resists abrasions, shrinking, and stretching, which makes it ideal for industrial applications such as conveyor belts, hoses, and heavy-duty fabrics.
- **Wrinkle resistant:** Polyester fabrics are naturally wrinkle-resistant, reducing the need for maintenance and ensuring a consistent appearance in applications like banners, industrial filters, and tents.
- **Quick drying:** Polyester's quick-drying properties are beneficial in industrial settings where materials are frequently exposed to moisture, such as in marine environments, industrial wiping cloths, and filtration systems.
- **Shape retention:** Polyester maintains its shape well, even under stress. This characteristic is crucial for applications that require dimensional stability, such as in automotive components, construction materials, and geotextiles.
- **Dimensionally stable:** Polyester retains its size and shape, resisting shrinkage and stretching. This stability is essential in industrial applications where consistent performance and reliability are critical.
- **Versatility:** Polyester can be blended with other materials to enhance its properties and broaden its range of applications. For instance, it can be combined with natural fibres to improve durability and functionality in industrial fabrics, ropes, and composite materials [12], [25], [38].

Some downsides to consider:

- **Low moisture absorbency:** Polyester's low moisture absorbency can be a drawback in applications where breathability is required, such as in certain types of protective clothing or covers.

- **Static cling:** Polyester can generate static electricity, which might be problematic in environments where static discharge needs to be minimized, such as in electronic manufacturing or cleanrooms.
- **Melts at high Temperatures:** Polyester has a lower melting point compared to some other materials. This characteristic must be considered in processes involving high heat, such as thermal bonding or high-temperature industrial applications.
- **Limited biodegradability:** Polyester is not biodegradable, raising environmental concerns. However, advancements are being made in creating more sustainable forms of polyester and improving recycling processes to address these issues [49-50].

2.2.3.4 Basalt fibre & its properties

Basalt isn't quite as common as nylon, polyester, or polypropylene, but it's an emerging player in the textile world. Basalt fibre is a relatively new textile option derived from volcanic rock (basalt). The basalt rock is crushed, melted at high temperatures (around 1500°C), and then extruded through tiny nozzles to form continuous filaments. Basalt fibre offers a compelling combination of strength, heat resistance, and eco-friendliness. As production scales up and costs come down, it has the potential to become a more prominent player in the textile industry, particularly for technical textiles and applications requiring high performance [12], [37], [38].

Important characteristics:

- **High strength and elasticity:** Basalt fibre boasts impressive tensile strength, even surpassing steel in specific strength (strength-to-weight ratio). This makes it valuable for applications that require high durability.
- **Heat resistant:** Basalt fibres can withstand very high temperatures, making them suitable for heat-resistant clothing, fire protection applications, and industrial uses.
- **Good insulator:** Basalt offers thermal and electrical insulation properties, making it useful in applications where temperature regulation or electrical insulation is needed.
- **Chemical resistance:** Basalt fibres are resistant to many chemicals and corrosion, adding to their durability and functionality in various settings.
- **Eco-friendly:** Basalt is a naturally occurring volcanic rock, making it a sustainable and environmentally friendly fibre option.

Some downsides to consider:

- Limited availability: Compared to more established fibres, basalt fibre production is still ramping up, so it might be less readily available.
- Cost: Due to their relatively new presence, basalt fibres can be more expensive than some conventional options.
- Abrasiveness: Basalt fibres can be slightly abrasive compared to some other textiles, so comfort needs to be considered in specific applications [12], [37].

2.2.3.5 Carbon fibre & its properties

Carbon fibre is a strong, lightweight material composed primarily of carbon atoms. These atoms are bonded together in a crystalline structure, creating a fibre that is exceptionally strong and stiff for its weight. The fibres are usually combined with other materials to form a composite, often used in high-performance products [11], [39]–[43].

Important properties:

- High strength-to-weight ratio: Carbon fibre is exceptionally strong relative to its weight. This property makes it ideal for applications where both strength and weight are critical factors.
- Stiffness: It has a high modulus of elasticity, meaning it is very stiff. This rigidity is advantageous in structural applications requiring minimal deformation under load.
- Corrosion resistance: Unlike metals, carbon fibre does not rust or corrode, making it suitable for use in harsh environments.
- Thermal expansion: Carbon fibre has a low coefficient of thermal expansion, meaning it does not expand or contract significantly with temperature changes. This stability is important in precision applications.
- Electrical conductivity: Carbon fibre can conduct electricity, which can be useful in specific applications, though it may also require insulation in certain scenarios to prevent unwanted conductivity.
- Fatigue resistance: It has excellent fatigue resistance, meaning it can withstand repeated loading and unloading cycles without significant degradation.
- Vibration damping: Carbon fibre can dampen vibrations, which is beneficial in applications where reducing vibration is crucial, such as aerospace and automotive components.

- Chemical resistance: It is resistant to many chemicals, making it durable in a variety of chemical environments.
- Thermal conductivity: While not as high as metals, carbon fibre does have good thermal conductivity, allowing it to dissipate heat effectively in certain applications.
- Aesthetic appeal: Carbon fibre has a distinctive appearance, often appreciated for its modern and high-tech look. This makes it popular for consumer goods like sporting equipment and luxury items.

2.2.3.6 Glass fibre & its properties

Glass fibre, also known as fibreglass, is a material made from extremely fine fibres of glass. It is widely used due to its advantageous properties, such as its high strength, lightweight, and durability. Here's an overview of glass fibre and its important properties [12], [44–46].

Composition and production:

Glass fibres are made by melting glass and then extruding it through fine holes to form thin filaments. These filaments are then gathered into threads or woven into fabrics. The main types of glass used in fibreglass production include:

1. E-glass (Electrical glass): The most common type, known for its good electrical insulation properties and high strength.
2. S-glass (Structural glass): Offers higher strength and modulus and is used in aerospace and high-performance applications.
3. C-glass (Chemical glass): Resistant to chemical corrosion, used in applications requiring chemical resistance.
4. AR-glass (Alkali-resistant glass): Contains zirconium dioxide for improved resistance to alkaline environments.

Important properties of glass fibre [12], [37], [47–49].

- High strength-to-weight ratio: Glass fibre is lightweight yet possesses a high tensile strength, making it ideal for applications where strength and low weight are crucial, such as in aerospace, automotive, and sporting goods.
- Durability: Glass fibres are resistant to moisture, many chemicals, and weathering, contributing to their long lifespan and low maintenance requirements.

- Electrical insulation: E-glass, in particular, has excellent electrical insulating properties, making it suitable for use in electronic and electrical applications.
- Thermal insulation: Glass fibres have low thermal conductivity, making them effective insulators against heat. This property is useful for building insulation and protective gear.
- Non-flammable: Glass fibre is non-combustible and has a high melting point, enhancing safety in applications exposed to high temperatures.
- Corrosion resistance: Glass fibre resists corrosion from water, salts, and other chemicals, which is beneficial in marine environments and chemical industries.
- Flexibility and versatility: Glass fibres can be woven into various fabrics or used in composite materials. This flexibility allows for a wide range of applications and easy integration into different manufacturing processes.
- Dimensional stability: Glass fibres maintain their shape and strength under various environmental conditions, providing reliability and consistency in performance.
- Acoustic insulation: Due to their structure, glass fibres can also provide sound insulation, making them useful in acoustic panels and soundproofing applications.

2.2.3.7 Aramid fibre & its properties

Aramid fibre is a class of heat-resistant and strong synthetic fibres. The name "aramid" is a shortened form of "aromatic polyamide," referring to its chemical structure, which includes aromatic (benzene) rings and amide bonds. Aramid fibres are commonly used in various applications where high strength, thermal stability, and chemical resistance are required [35], [37].

Important properties of aramid fibre:

- High strength-to-weight ratio: Aramid fibres have a high tensile strength, making them stronger than steel on a per-weight basis. This makes them ideal for applications where lightweight strength is essential.
- Thermal stability: They can withstand high temperatures without degrading. Aramid fibres have a decomposition temperature above 500°C (932°F) and do not melt, which makes them suitable for high-temperature applications.
- Flame resistance: Aramid fibres are inherently flame-resistant and do not catch fire easily. They do not melt or drip, which adds to their safety in high-heat environments.

- Chemical resistance: Aramid fibres resist degradation from many chemicals, including organic solvents, oils, and fuels. This property makes them useful in harsh chemical environments.
- Electrical insulation: They are non-conductive, which makes them good insulators and useful in electrical and electronic applications.
- Low creep: Aramid fibres exhibit minimal creep (the tendency to deform under long-term stress), which ensures dimensional stability over time.
- Impact resistance: They have high impact resistance, making them useful in protective gear and ballistic applications.
- Durability: Aramid fibres are known for their long-term durability and resistance to abrasion, contributing to their longevity in various applications.

2.2.4 Matrix Material

In composite materials, the matrix is the continuous phase that surrounds and supports the reinforcement fibres or particles, providing their shape and protecting them from environmental damage [11], [23], [50], [51]. The primary role of the matrix is to transfer the load to the reinforcement material, distribute stress, and provide ductility to the composite. The matrix material can be metallic, ceramic, or polymeric. In the context of fibre-reinforced composites, the matrix is typically a polymer, which can be categorized into two main types: thermoplastic and thermoset resins.

Thermoplastic resins are a type of polymer that becomes soft and mouldable upon heating and hardens when cooled, a process that can be repeated multiple times without significant degradation. This reversible process allows for reshaping and recycling, making thermoplastics highly versatile [61]. They are known for their toughness, impact resistance, and chemical resistance, making them suitable for a wide range of applications, including automotive parts, consumer goods, packaging, medical devices, and aerospace components. Common examples of thermoplastic resins include polyethylene (PE), polypropylene (PP), polyamide (nylon), polycarbonate (PC), etc.

Thermoset resins, on the other hand, undergo an irreversible curing process that creates a cross-linked molecular structure, making them rigid and stable once set. Unlike thermoplastics, they cannot be melted and reshaped after curing. This chemical reaction provides thermosets with high thermal stability, excellent dimensional stability, and superior mechanical properties, such as high strength and stiffness [20], [41], [52-54].

Due to these characteristics, thermoset resins are ideal for high-performance applications requiring durability and resistance to high temperatures and chemicals. Common examples include epoxy, polyester, vinyl ester, phenolic resins, etc. which are widely used in the aerospace, marine, electronics, automotive, and construction industries.

2.2.4.1 Polyester (unsaturated)

These matrices are used in the transportation, construction, and medical industries. Unsaturated polyester has excellent performance, low cost, and great process versatility.

2.2.4.2 Vinyl ester

The properties of vinyl Ester are similar to those of polyester. Excellent mechanical and fatigue properties, excellent chemical resistance, and major uses are corrosion applications where the chances of corrosion are high, such as pipes, tanks, and ducts, In all these places, vinyl ester is used as matrix material.

2.2.4.3 Phenolic

The phenolic matrix material is excellently fire-resistant, so it is used where a requirement for fire-resistant products exists. It has low smoke and toxic emissions. It also has high strength at high temperatures, so we can use it for high-temperature applications like mass transit ducting, fire-resistant, high-temperature, etc.

2.2.4.4 Polyurethane

The characteristic of polyurethane is that it is tough, has good impact resistance, and has good surface quality. So, polyurethane matrices are used in bumper beams and automotive panels, where we need toughness and good impact resistance.

2.2.4.5 Epoxy and its characteristics

Epoxy resins have excellent mechanical properties. Good fatigue resistance, low shrinkage, good heat and chemical resistance, and major applications of fibre-reinforced polymer strengthening systems. So it is used in the application of reinforcing bars. Epoxy resin is a type of thermosetting polymer that is widely used as a matrix material in composite materials due to its excellent mechanical properties, thermal stability, and chemical resistance. Some of the important characteristics of epoxy resin include [23], [54], [55].

- High strength and stiffness: epoxy resins offer exceptional mechanical properties, such as high strength and stiffness, which make them ideal for use in applications requiring load-bearing structural components.
- Good adhesion: Epoxy resins exhibit excellent adhesion to various materials, including metals, plastics, and composites, making them a popular choice for bonding and repair applications.
- Chemical resistance: Epoxy resins are highly resistant to a wide range of chemicals, including acids, bases, solvents, and fuels, making them suitable for use in harsh environments.
- Excellent electrical insulation properties: Epoxy resins have good electrical insulation properties, making them ideal for use in electrical and electronic components.
- Low shrinkage: Epoxy resins exhibit low shrinkage during curing, resulting in minimal internal stresses and improved dimensional stability.
- Temperature resistance: Epoxy resins have good thermal stability and can withstand high temperatures, making them ideal for use in high-temperature applications.
- Easy to process: Epoxy resins are easy to process and can be molded into a variety of shapes and sizes, making them suitable for a wide range of applications.
- UV resistance: Epoxy resins are resistant to UV radiation, making them ideal for use in outdoor applications where exposure to sunlight is a concern.

2.2.5 Braided Composites

Braided composites are an important and increasingly popular type of textile composite that offers a wide range of possibilities for various industries and applications. Braided composites are a type of textile composite in which the reinforcement material is braided instead of woven or knitted. Braiding involves interlacing yarns or fibres in a diagonal pattern around a central axis, creating a tubular structure. The braided structure provides the reinforcement for the composite material, while the matrix material, usually a polymer resin, fills the voids between the fibres, providing support and binding the structure together.

Braided composites offer several advantages over other types of composites, including high strength and stiffness, excellent impact resistance, and good damage tolerance [9], [12], [16], [56–61]. The braided structure provides a continuous fibre path, which helps

distribute loads evenly across the structure, reducing stress concentrations and enhancing overall strength. The braided structure also allows for a high degree of customization, as the angle and the number of fibre bundles can be adjusted to meet specific requirements.

Braided composites are commonly used in aerospace, automotive, and sporting goods applications, such as aircraft components, vehicle body panels, and high-performance tennis rackets. The unique properties of braided composites make them well-suited for applications that require high strength, stiffness, and durability, combined with lightweight construction [2], [14], [62].

2.3 Textile Products for Civil Engineering Application

The use of textile products in civil engineering is becoming increasingly popular due to their lightweight, high-strength, and cost-effective properties. They offer a sustainable and innovative alternative to traditional building materials, allowing for creative and unique designs that are also environmentally friendly. Some of the applications of textile products in civil engineering include [6], [12], [28], [47], [63–68].

Geotextiles:

Geotextiles are permeable textile materials used in civil engineering applications for soil stabilization, drainage, and erosion control. They are commonly used in road construction, railway embankments, and retaining walls (Figure 2.11).



Figure 2.11 Application of geotextile in road building

Geogrids:

Geogrids are high-strength woven or knitted textiles used to reinforce soils and improve their bearing capacity. They are commonly used in slope stabilization, retaining walls, and reinforcement of soft soils (Figure 2.12).



Figure 2.12 Application of geogrids

Geomembranes:

Geomembranes are impermeable membranes made from textiles or other materials used in civil engineering applications for containment and barrier systems. They are commonly used in landfill liners, water storage facilities, and canals (Figure 2.13).



Figure 2.13 Application of geomembranes

Reinforcement of concrete:

Textile materials such as carbon fibre, glass fibre, and basalt fibre can be used to reinforce concrete structures. They improve the strength and toughness of the concrete, reducing the likelihood of cracking and increasing the durability of the structure (Figure 2.14).

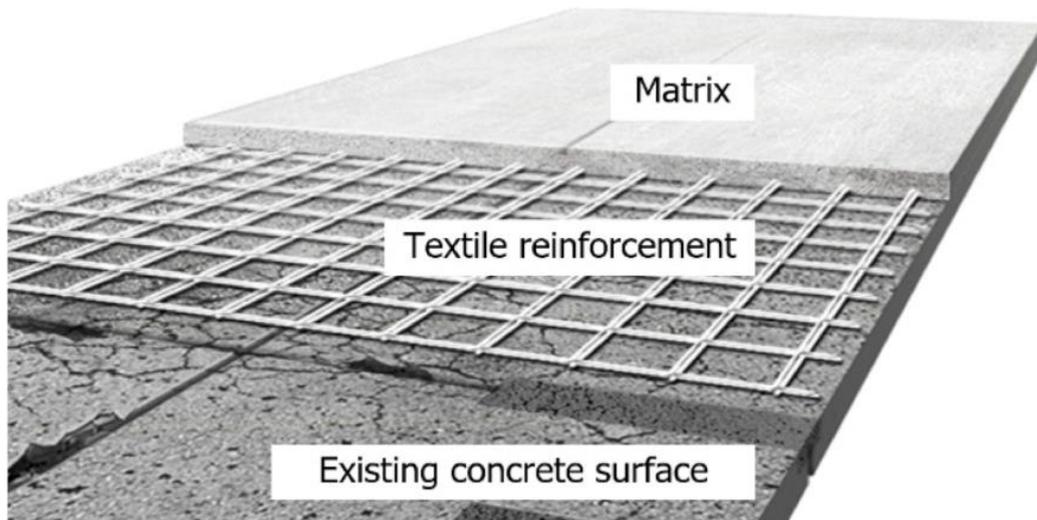


Figure 2.14 Application as reinforcement material

Tensile structures:

Textile materials such as PVC-coated polyester and PTFE-coated fibre glass can be used to create lightweight tensile structures, such as roofs and canopies. These structures offer a cost-effective and aesthetically pleasing alternative to traditional construction materials (Figure 2.15).



Figure 2.15 Textile material application as Tensile Structures

Architectural membranes:

Textile membranes can be used to create architectural features, such as facades and roofs. They offer a lightweight and flexible alternative to traditional building materials and allow for unique and creative designs (2.16).



Figure 2.16 Textile material application as Architectural membranes

Reinforcement of masonry:

Textile materials such as carbon fibre can be used to reinforce masonry structures, such as historic buildings, bridges, and monuments. They improve the strength and durability of the masonry, reducing the likelihood of collapse and increasing the lifespan of the structure (Figure 2.17).

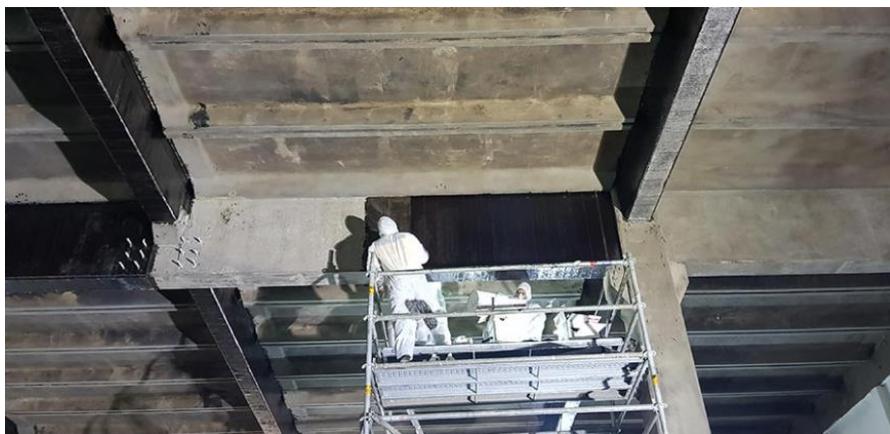


Figure 2.17 Textile material application as reinforcement masonry

2.4 Reinforcement Bars

Reinforcement bars, also known as rebar, are steel bars used to reinforce concrete structures. Concrete is strong in compression but weak in tension, and reinforcement bars are used to resist tensile stresses in the structure. Reinforcement bars are made from carbon steel, and they come in different sizes and shapes, depending on the specific application. The most common shapes of reinforcement bars are round and deformed. Deformed bars have a ridged surface that provides better bonding with concrete [81 - 83]. Reinforcement bars are used in a wide range of concrete structures,

including buildings, bridges, tunnels, and highways. They are placed in a grid pattern within the concrete as shown in Figure 2.18 to provide the necessary strength and stability to the structure.



Figure 2.18 Grid pattern of reinforcement bars

The process of reinforcing a concrete structure with reinforcement bars involves several steps, including designing the structure, determining the required size and spacing of the bars, placing the bars in the correct position, and securing them in place with wire ties or spacers. Once the reinforcement bars are in place, concrete is poured around them to form the final structure.

Proper installation and placement of reinforcement bars are critical to the strength and durability of the concrete structure. Reinforcement bars that are not properly installed or spaced can lead to structural failure or collapse [34], [69–71]. Therefore, it is essential to follow the required standards and guidelines for the installation of reinforcement bars in concrete structures.

Steel rebar's' tensile strength characteristics vary based on diameter and steel grade. For commonly used grades like ASTM A615, Grade 40 has a yield strength of 280 MPa and tensile strength of 420 MPa, Grade 60 has 420 MPa yield and 620 MPa tensile strength, and Grade 75 has 520 MPa yield and 690 MPa tensile strength. For specific diameters, rebar typically exhibits the following properties: 3 mm rebars have a yield strength of around 420 MPa and tensile strength of 620 MPa, while 6 mm, 8 mm, 10 mm, and 12 mm rebar, often made from Grade 60 steel, share these same values [72].

2.4.1 Important Characteristics of Rebar

The characteristics of bars in civil engineering are essential to ensuring the durability and safety of reinforced concrete structures. The properties of reinforcement bars are

carefully considered and specified by civil engineers in the design process to ensure that the structure will perform as intended and withstand the forces it will be subjected to over its lifespan. Some of the important characteristics of bars in civil engineering include [73]–[79]:

1. **Tensile strength:** Reinforcement bars need to have high tensile strength to withstand the tensile forces that occur in a reinforced concrete structure. The bars are placed in the concrete to take on the tensile loads and prevent cracking and failure of the structure.
2. **Ductility:** Bars must have good ductility to prevent sudden failure in the structure. Ductility allows the bars to elongate and deform under tensile forces without breaking.
3. **Bond strength:** The bond strength between the reinforcement bars and concrete is critical to the performance of the reinforced concrete structure. The bond strength depends on factors such as surface area, rib pattern, and quality of the concrete.
4. **Corrosion resistance:** Reinforcement bars are often exposed to corrosive environments, which can cause the bars to weaken and fail over time. To prevent this, bars must have good corrosion resistance and be protected with an appropriate coating or surface treatment.
5. **Bendability:** Reinforcement bars must be bendable so that they can be shaped and placed in the concrete as required by the design.
6. **Weldability:** Welding is often used to join reinforcement bars together, so bars must have good weldability to ensure strong and reliable connections.
7. **Cost-effectiveness:** Reinforcement bars must be cost-effective and readily available to ensure that they can be used in large quantities in construction projects.

2.4.2 Pros and Cons of Steel Rebar

Steel reinforcement bars remain the most widely used material for reinforcement in concrete structures due to their high strength, ductility, and availability. However, their susceptibility to corrosion and fire, as well as environmental concerns, have led to the development and use of alternative reinforcement materials such as fibre-reinforced polymers (FRP) and basalt fibres.

Some of the pros and cons of using steel reinforcement bars are [5], [24], [66], [71], [74], [76], [80–82].

Pros:

1. *High strength:* Steel has a high strength-to-weight ratio, making it an ideal material for reinforcing concrete structures.
2. *Ductility:* Steel can deform without breaking, which allows it to absorb energy and resist sudden failures due to extreme loads or environmental factors.
3. *Bond strength:* Steel has a good bond strength with concrete, which helps to transfer loads between the two materials.
4. *Cost-effective:* Steel reinforcement bars are widely available and cost-effective, making them a popular choice for construction projects.
5. *Durability:* When properly protected from corrosion, steel reinforcement bars have a long service life and can provide durable reinforcement for concrete structures.

Cons:

1. *Corrosion:* Steel reinforcement bars are prone to corrosion, especially in aggressive environments such as coastal areas, where salt and moisture can accelerate the corrosion process (Figure 2.19).
2. *Susceptible to fire:* Steel loses strength rapidly when exposed to high temperatures, which can compromise the structural integrity of the reinforced concrete structure.
3. *Weight:* Steel reinforcement bars are heavy, which can make them difficult to handle and transport.
4. *Environmental concerns:* Steel production and processing can have significant environmental impacts, including greenhouse gas emissions and the consumption of natural resources.
5. *Magnetism:* Steel reinforcement bars are magnetic, which can interfere with certain sensitive equipment or applications.



Figure 2.19 Corrosion of steel rebars

2.4.3 Fibre Reinforcement Rebars

Fibre reinforcement bars are a type of composite material that are used as an alternative to traditional steel reinforcement bars in concrete structures (Figure 2.20). They are typically made from fibres such as glass, carbon, or basalt, which are embedded in a matrix material such as polymer or cement. Some of the pros and cons of fibre reinforcement bars [24], [73], [75], [81–84].



Figure 2.20 Fibre reinforcement rebars

Pros:

1. *Corrosion resistance:* Fibre reinforcement bars do not corrode, which makes them an ideal choice for structures that will be exposed to harsh environments, such as bridges, parking garages, and marine structures.
2. *Lightweight:* Fibre reinforcement bars are lighter than steel, which makes them easier to handle and transport.
3. *High strength-to-weight ratio:* Fibre reinforcement bars have a high strength-to-weight ratio, which makes them stronger than steel on a per-weight basis.
4. *Easy to install:* Fibre reinforcement bars can be easily cut and shaped on-site, which makes them easy to install.
5. *Electromagnetic neutrality:* Fibre reinforcement bars are non-magnetic, which makes them ideal for use in sensitive electronic environments.

Cons:

1. *Cost:* Fibre reinforcement bars can be more expensive than traditional steel reinforcement bars, which can make them cost-prohibitive for some projects.

2. *Brittle behavior*: Unlike steel, which is ductile and can deform without breaking, fibre reinforcement bars have a brittle behavior and can fail suddenly and without warning.
3. *Fire resistance*: Some fibre reinforcement bars are not as fire-resistant as steel, which can be a concern in certain applications.
4. *Adhesion*: The adhesion between the fibre reinforcement bar and the surrounding concrete may not be as strong as the adhesion between steel and concrete, which can affect the load-carrying capacity of the structure.

FRP (Fibre-Reinforced Polymer) rebar is increasingly used in construction due to its high strength-to-weight ratio, corrosion resistance, and non-conductive properties.

2.5 Comparison Between Steel Rebar and FRP Bars

Fibre-reinforced polymer (FRP) rebar offers several advantages over conventional steel rebar, addressing some of the limitations associated with steel reinforcement. Following are some ways in which FRP rebar's are better [4], [5], [64], [66], [74], [76], [77], [85], [86]:

1. *Corrosion resistance*: FRP rebar's are non-metallic and do not corrode like steel rebars. This makes them highly resistant to deterioration caused by moisture, chloride ions, and other aggressive chemicals. As a result, structures reinforced with FRP rebars have a longer service life and require less maintenance and repair.
2. *Lightweight*: FRP rebar is significantly lighter than steel rebar, typically weighing about one-fourth the weight of steel for the same strength. The lightweight nature of FRP rebars simplifies handling, transportation, and installation on construction sites. It can also reduce the dead load of the structure, leading to potential cost savings in the design and construction of the supporting elements.
3. *High strength-to-weight ratio*: FRP rebars have a high strength-to-weight ratio, meaning they are stronger than steel rebars of the same weight. This allows for the design of more slender and lightweight structures without compromising strength or safety.
4. *Non-magnetic and non-conductive*: FRP rebars are non-magnetic and non-conductive, which makes them suitable for applications in sensitive environments, such as medical facilities or areas with electromagnetic interference (EMI)

concerns. They do not interfere with electronic devices, and their non-conductive nature can enhance electrical safety.

5. **Thermal insulation:** FRP rebar's have lower thermal conductivity compared to steel rebars. This property helps reduce thermal bridging and can contribute to improved energy efficiency in buildings and structures.
6. **Design flexibility:** FRP rebars can be easily shaped and customized to meet specific design requirements. They can be manufactured in various sizes, shapes, and configurations, enabling greater flexibility in architectural and structural design. FRP rebars can also be bent on-site, allowing for easier installation around corners and curved elements.

While FRP rebars offer several advantages, it's important to consider certain factors when deciding to use them. These factors include cost, fire resistance, creep behavior, and code acceptance, as FRP materials may have different design guidelines and standards compared to conventional steel reinforcement [103-106]. Table 2.1 compares tensile characteristics of steel rebars with FRP rebars.

2.6 Work Reported So Far

Research in the field of composite textile fibre reinforcement bars has focused on various aspects such as mechanical properties, durability, long-term performance, manufacturing techniques, bond behavior, cost-effectiveness, and sustainability. These studies aim to enhance the understanding, performance, and application of composite textile reinforcement bars in construction and civil engineering projects.

Studies have been conducted on mechanical properties to understand the tensile, flexural, and shear behaviour of composite textile reinforcement bars compared to traditional steel reinforcement. Research has also investigated the resistance of composite textile reinforcement bars to corrosion, fatigue, and environmental degradation over time, keeping in mind durability and long-term performance. Various manufacturing methods for producing composite textile reinforcement bars have been explored, including pultrusion, weaving, and braiding processes. Studies have looked into the adhesion and bond strength between composite textile reinforcement bars and concrete to assess their effectiveness in structural applications. Cost-effectiveness and sustainability: Research has also considered the economic feasibility and environmental

benefits of using composite textile reinforcement bars compared to conventional steel bars.

Table 2.1 Comparison between steel rebar and FRP bars [103 – 112]

Sr. No	Diameter (mm)	Material	Tensile Strength (MPa)	Reference Standard
1	4	GFRP	600 - 800	ACI 440.6M-08, CSA S807-10
2	4	CFRP	1200 - 1500	ACI 440.6M-08, CSA S807-10
3	4	AFRP	1000 - 1200	ACI 440.6M-08, CSA S807-10
4	4	Steel (Grade 60)	620	ASTM A615
5	6	GFRP	700 - 900	ACI 440.6M-08, CSA S807-10
6	6	CFRP	1300 - 1600	ACI 440.6M-08, CSA S807-10
7	6	AFRP	1100 - 1300	ACI 440.6M-08, CSA S807-10
8	6	Steel (Grade 60)	620	ASTM A615
9	8	GFRP	800 - 1000	ACI 440.6M-08, CSA S807-10
10	8	CFRP	1400 - 1700	ACI 440.6M-08, CSA S807-10
11	8	AFRP	1200 - 1400	ACI 440.6M-08, CSA S807-10
12	8	Steel (Grade 60)	620	ASTM A615
13	10	GFRP	900 - 1100	ACI 440.6M-08, CSA S807-10
14	10	CFRP	1500 - 1800	ACI 440.6M-08, CSA S807-10
15	10	AFRP	1300 - 1500	ACI 440.6M-08, CSA S807-10
16	10	Steel (Grade 60)	620	ASTM A615
17	12	GFRP	1000 - 1100	ACI 440.6M-08, CSA S807-10
18	12	CFRP	1600 - 2000	ACI 440.6M-08, CSA S807-10
19	12	AFRP	1400 - 1500	ACI 440.6M-08, CSA S807-10
20	12	Steel (Grade 60)	620	ASTM A615

Prof. Antonio Nanni's investigations serve as a vital conduit between theoretical research and practical application in the construction industry. His meticulous examination of variables such as concrete composition and environmental exposure informs guidelines for the usage of FRP (fiber-reinforced polymer) bars, offering engineers nuanced insights into bond strength. By scrutinizing sustained loads, thermal cycles, and chemical exposure, Prof. Nanni's work ensures the durability and structural integrity of FRP bars under diverse conditions. Moreover, Prof. Nanni champions sustainability within the industry, advocating for the incorporation of recycled materials in FRP production. This approach not only mitigates environmental impact but also promises economic benefits through reduced maintenance costs. By demonstrating that sustainable practices can harmonize economic and ecological interests, he presents a compelling case for their adoption in construction projects. Prof. Nanni's research stands as a testament to the symbiotic relationship between scientific inquiry and practical engineering, bridging the gap between abstract theory and tangible outcomes. His contributions advance the field of construction materials and techniques, empowering engineers to make informed, evidence-based decisions that prioritize both performance and sustainability [12], [45], [82], [84].

Prof. Anastasios Vassilopoulos's expertise in filament winding techniques represents a pioneering force in the realm of construction materials. His meticulous control over winding patterns and tension aims to produce defect-free FRP (fiber-reinforced polymer) bars, while his advancements in automated systems expedite production rates. Vassilopoulos's relentless pursuit of perfection ensures that FRP bars are not only of impeccable quality but are also produced with unprecedented efficiency, thus revolutionizing modern construction practices [27]. In parallel, Dr. Sami Rizkalla's comprehensive life-cycle cost analyses offer critical insights into the economic viability of FRP bars. Despite their initially higher costs, Rizkalla's analyses reveal substantial long-term savings due to reduced maintenance requirements, presenting FRP bars as a cost-effective option over their lifespan. By advocating for a holistic view that considers the entire life cycle of construction materials, Rizkalla underscores the importance of balancing upfront expenses with long-term benefits [12], [82].

Prof. Vistasp M. Karbhari and Prof. Lawrence C. Bank contribute significantly to the discourse on the environmental advantages of FRP bars. Their work highlights the

potential of these materials to dramatically lower the carbon footprint of construction projects. By emphasizing the integration of recycled materials into FRP production, Karbhari and Bank align sustainability goals with economic efficiency, demonstrating how environmental responsibility can concurrently achieve cost savings [12], [74], [87], [88].

Dr. Brahim Benmokrane's extensive research is a cornerstone in the field of construction materials, focusing on the long-term performance and durability of FRP (fiber-reinforced polymer) bars in concrete structures. His meticulous studies reveal the longevity and reliability of these bars under various environmental exposures, such as alkaline conditions, temperature fluctuations, and moisture. These environmental factors positively influence the mechanical properties and overall durability of FRP bars, ensuring their resilience and effectiveness in reinforcing infrastructure. Delving deeper into the critical interaction between FRP bars and concrete, Dr. Benmokrane examines the impact of surface treatments and material types. His findings provide essential insights that enhance the performance of FRP bars within concrete structures, emphasizing the necessity for tailored solutions that optimize the bond between these materials. This work is pivotal in ensuring the long-term durability and structural integrity of reinforced concrete systems. In addition to performance enhancement, Dr. Benmokrane's exploration of alternative, low-cost fibers and resins highlights the potential for significantly reducing production costs and carbon emissions associated with FRP bars. His innovative approach encourages a balance between affordability and environmental sustainability, offering a dual benefit to construction industry stakeholders and the planet. Dr. Benmokrane's dedication to advancing FRP technology underscores the importance of combining technical excellence with environmental consciousness. His research not only reinforces infrastructure but also advocates for a more sustainable and economically viable construction industry, paving the way for future advancements that prioritize both durability and ecological responsibility [12], [44], [89–91].

Dr. J. G. Dai's research is pivotal in advancing the application of FRP (fiber-reinforced polymer) bars, particularly in marine environments where corrosion resistance and long-term mechanical properties are critical. His findings advocate for the use of FRP bars in harsh conditions, underscoring their durability and reliability in coastal

structures. By fortifying these structures, Dr. Dai ensures that FRP bars can withstand the corrosive challenges posed by saltwater, enhancing the longevity of marine infrastructure. Further exploring the durability of FRP bars, Dr. Dai delves into the mechanisms of bond degradation over time. His comprehensive analysis of these processes informs strategies aimed at improving the long-term bond performance of FRP-reinforced concrete structures. This work is crucial in maintaining the structural integrity and durability of such systems, highlighting the importance of continuous research and innovation. Dr. Dai's insights underscore the necessity of sustainable infrastructure development, emphasizing that ongoing research and adaptation are vital to safeguarding our built environment for future generations. His contributions to the field not only enhance the performance and resilience of FRP bars but also exemplify the essential role of scientific inquiry in the pursuit of sustainable construction practices [92-93].

Dr. Mohamed Masmoudi's research offers critical insights into the degradation mechanisms of FRP (fiber-reinforced polymer) composites under the influence of moisture, temperature variations, and chemical exposure. His comprehensive analysis deepens our understanding of the long-term performance of these materials, equipping engineers to anticipate and mitigate potential challenges over time [12], [44], [89], [91].

Prof. L. C. Bank's meticulous evaluation of the creep behavior, thermal effects, and environmental aging of FRP composites further enhances our comprehension of their lifespan and reliability. His rigorous research ensures that FRP bars maintain their structural integrity throughout their service life, providing a robust foundation for their application in various construction projects [12], [74], [87], [88].

Dr. Mirmiran's focus on creep behavior, stress relaxation, and fatigue resistance in FRP bars used in bridge construction is particularly illuminating. By investigating their performance under extended periods and varying loading conditions, Dr. Mirmiran's work assures that bridges reinforced with FRP bars can withstand the test of time, demonstrating exceptional resilience [12], [24].

Prof. Rao's emphasis on the superior resistance of FRP bars to diverse environmental conditions, including freeze-thaw cycles, UV exposure, and chemical aggressions, underscores the long-term durability of these materials. His research empowers

engineers to select FRP bars that will endure even the most challenging environments, ensuring sustained performance and reliability [12].

Dr. Scott T. Smith's valuable research centers on optimizing bond strength in FRP (fiber-reinforced polymer)-reinforced structures under diverse concrete compositions and loading conditions. His findings significantly enhance the reliability and performance of these structures, emphasizing the necessity of tailoring FRP applications to meet specific project requirements. This approach ensures robust performance throughout the service life of the structures. Delving into the effects of sustained loading and environmental interactions with concrete, Dr. Smith's studies provide crucial insights into the durability factors that influence the long-term performance of FRP bars. His comprehensive analysis informs strategies to safeguard the structural integrity of FRP-reinforced systems, underscoring the critical role these bars play in ensuring the longevity of our built environment. Dr. Smith's research exemplifies the intersection of meticulous scientific investigation and practical engineering application. By focusing on the nuanced interplay between materials and environmental factors, his work contributes to the development of more resilient and durable infrastructure, advancing the field of construction materials and techniques [12], [75].

Prof. Vadim V. Silberschmidt's studies on hybrid FRP bars highlight their potential for enhanced bond strength and durability. His innovative approach paves the way for resilient composite reinforcement solutions, inspiring further exploration of novel materials and designs that elevate the performance of FRP-reinforced concrete. Prof. Silberschmidt's rigorous assessment of the fatigue behavior, impact resistance, and long-term stability of FRP (fiber-reinforced polymer) composites offers a comprehensive understanding of their lifecycle performance. His insights guide the development of robust and enduring materials, fostering sustainable construction practice [94–97].

Dr. Yasuhiko Watanabe pioneers the development of hybrid FRP composites with enhanced durability. By improving resistance to environmental degradation and mechanical wear, he ensures their long-term performance. His innovations fortify our structures, seamlessly combining strength and resilience [98].

Dr. Satish Kumar's focus on refining the pultrusion process is pivotal to enhancing the mechanical properties and manufacturing efficiency of FRP bars. By optimizing production parameters and exploring advanced resin systems, Dr. Kumar ensures that FRP bars meet stringent quality standards, reinforcing infrastructure with reliable materials [99].

Dr. Habib Tabatabai's pioneering work with techniques such as Resin Transfer Molding (RTM) and Vacuum-Assisted Resin Infusion (VARI) results in FRP bars with superior mechanical properties and reduced void content. His innovative methods push the boundaries of material science, contributing to stronger and more reliable structural reinforcements [100].

Prof. John Summerscales's expertise in automated fiber placement and tape laying fine-tunes the manufacturing processes of FRP bars. His precision engineering enhances mechanical performance, ensuring that FRP bars meet demanding load requirements, and contributes to the creation of safer and more resilient structures [101].

Dr. Thomas Keller's exploration of thermoplastic composites introduces recyclability and processing efficiency to reinforcement bars. These materials offer significant performance advantages while minimizing environmental impact. Dr. Keller's sustainable approach aligns with the responsibility to build resilient infrastructure while reducing our ecological footprint [12], [68], [96], [102].

Prof. Ryszard J. Zalewski's innovations in braided and woven fiber architectures significantly enhance the durability and production efficiency of FRP (fiber-reinforced polymer) bars. His work on automation ensures consistent quality, revolutionizing concrete reinforcement. Prof. Zalewski exemplifies progress, creating FRP bars that are stronger, produced faster, and crafted smarter to meet the demands of a dynamic world [103].

Dr. Ashfaq Adnan's exploration of additive manufacturing opens new horizons for the construction industry. By enabling complex geometries and customized solutions, Dr. Adnan expands the design possibilities for FRP bars, propelling the field toward adaptable, bespoke reinforcement solutions tailored to each project's unique demands [104].

Prof. Luigi Ascione pioneers hybrid manufacturing techniques that result in multifunctional composite bars. His work bridges the gap between tradition and innovation, ensuring that FRP bars can seamlessly adapt to diverse engineering challenges, offering tailored solutions for specific applications [12], [105].

Dr. P. Michael Schubel's focus on rapid manufacturing optimizes cycle time and energy consumption. By balancing efficiency with mechanical properties, Dr. Schubel accelerates construction timelines, aligning his approach with the urgency of modern infrastructure demands [106].

Prof. Peter Davies champions eco-friendly methods, utilizing bio-based resins and natural fibers to create sustainable composite materials. His commitment to environmental stewardship ensures that structures maintain high performance while respecting ecological considerations, proving that durability need not compromise the planet [107].

2.7 Research Gap and Objectives

Steel has long been essential in the construction industry for reinforcement purposes. However, its susceptibility to corrosion, heavy weight, and low strength-to-weight ratio pose significant limitations. Additionally, steel's environmental sensitivity, high thermal conductivity, electric conductivity, and limited design flexibility further restrict its applications. On the other hand, Fiber Reinforced Polymer (FRP) rebars, typically made using a wrapping technique are costly and present their own challenges. These rebars may snap rather than bend under pressure and possess a low modulus of elasticity, resulting in insufficient rigidity and easy deformation.

Looking at these issues, there is a great need for comprehensive research on the long-term behavior and durability of FRP bars made from braided ropes and resin materials under extreme environmental conditions. Furthermore, a thorough understanding of the bond behavior between FRP bars and concrete is essential for the effective utilization of FRP reinforcements in structural applications. Optimizing bond strength and addressing potential bond-related issues are crucial areas of focus. Braided composite rods are expected to offer structural benefits and enhanced bond and tensile strength due to the intertwining of yarns, making them a promising alternative. Research aimed at reducing the overall cost of FRP bars including manufacturing processes, material

sourcing, and installation techniques which is vital for making FRP reinforcements more economically competitive with steel.

Addressing these research gaps will significantly advance the understanding and broader acceptance of FRP bars as a viable alternative to traditional steel reinforcements in civil engineering and construction applications.