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REVIEW

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# A Comprehensive Review of Braided Structures: Evolution, Structural Mechanics, Applications, and Market Trends

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## Abstract

**Purpose:** This review provides a comprehensive understanding of braided structures by examining their historical evolution, geometric characteristics, braiding methodologies, structural mechanics, material selection, industrial applications, and global market trends. It also compares braiding with other conventional fabric formation techniques to highlight its structural and functional advantages.

**Methodology/Design:** A comprehensive review of literature available in print media, historical documents, technical reports, and industrial information was conducted. Sources from textile engineering, materials science, medical textiles, composite materials technology, etc., were critically examined to arrive at a synthesised body of knowledge on aspects such as braid geometry, mechanics of braiding processes, fibres used in braiding, behaviour of braiding materials, etc.

**Findings:** Braided materials show good mechanical properties, continuity of fibres, conformability, and fatigue resistance when compared to other textile materials. Recent developments in braiding technology, such as CNC and 3D braiding machines, allow the creation of complex near-net-shape products for use in the aerospace, automotive, civil, and biomedical industries. Market research has shown that the demand for braided composite materials and braiding machines continues to increase owing to the growing need for technical textiles.

**Practical and Social Implications:** A clear and precise knowledge of the geometry and parameters of braids and the variables of the braiding process can help engineers and makers design braiding systems that can be tailored to suit specific functional requirements. A knowledge of the contemporary machinery and the market can also be helpful in making decisions about investments and product development.

**Originality:** This review uniquely integrates the historical foundations, structural science, technological advancements, application spectrum, and market perspectives of braiding within a single framework. By bridging classical textile principles with modern digital manufacturing and composite innovations, the study establishes braiding as a strategically important and future-oriented textile technology for high-performance engineering applications.

**Keywords**
Braiding, historical evolution, braid unit cell, structural geometry, performance evaluation

## 1 | INTRODUCTION

Braiding is a distinct and unique type of textile fabric. Braiding, according to the Encyclopaedia Britannica, is the interlacing of three or more yarns that cross each other diagonally to form flat or tubular fabric strips (Brunnschweiler, 1953). While different methods can be used to manufacture braids where the basic structure of braiding remains constant. Alagirusamy & Padaki define braiding as a textile manufacturing process that is used to manufacture fabrics through intertwining of yarns to form a ribbon-like or rope-like textures in a way that prevents adjacent threads from making full turns around each other (Alagirusamy & Padaki, 2015). Today, braiding is a highly affordable method for producing fabric (Kostar & Chou, 1999; Kyosev, 2015). Braided structures are rapidly gaining popularity in the textile industry, where they are widely used in the production of technical textiles and composite materials. Due to its simplicity and cost-effectiveness, braiding has evolved into an important method for manufacturing technical textiles and composite reinforcements. In recent decades, braided structures have gained

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significant attention in high-performance applications. Notably, industry heavyweights like NASA and Boeing have used 3D braided carbon fibre components for aerospace applications, while biomedical companies use braided nitinol and polymer materials in vascular implants and catheters (Chellamani et al., 2013; Masters et al., 1994; Mikhailov, 1993; Saha et al., 2025a). Braided materials are commonly used in sports equipment such as baseball bats, parachute cords, fishing lines and fishing nets, climbing ropes, and bicycle frames. Braids are also used for lifting and winching, shipping, forestry, electrical wires, hoses, shoelaces, and other applications (Hamouda et al., 2020).

There are many different types of braid structures: flat, soutache, tubular, square, special (fancy or lace), 3D rectangular, and 3D tubular. The most common types are flat and tubular braids. There are two main types of motion in any braiding machine: linear and rotational. The braid structure is formed by rotating components, and the "take-up" process is facilitated by linear motion. The construction of braids is based on this interlacing mechanism. Braid mechanical properties are greatly affected by various yarn interlacing patterns, such as Diamond (1/1), Regular (2/2), and Hercules (3/3). Furthermore, it is possible to generate patterns such as 2/1, 3/1, and 3/2 interlacements (Bicking & Oxenham, 2012; Brunnschweiler, 1953; Hamouda et al., 2020; Pei et al., 2019). The geometry of the braid structure is dependent on numerous factors, including pick count, diameter, and braid angle (Omeroglu, 2006; Rawal et al., 2005; Saha et al., 2025b). A typical braid geometry has been shown in Figure 1, consists of the braiding axis, line (L), stitch (S), and braiding angle (θ). Picks or plaits, also called stitches defined the make-up of the braid. One repetition of the braid structure perpendicular to the braid axis is referred to as a line. The number of carriers in the braiding machine is correlated with the number of lines in a braided structure.

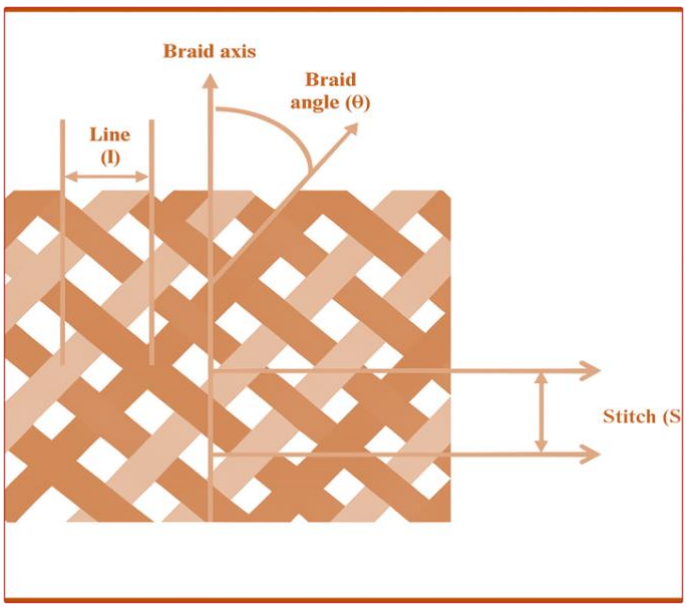



**Figure 1.** Illustrative diagram of a braid structure (source: authors own work)

As per Rawal et al. (2005), the braid angle is represented by half of the angle created between the interlacing yarns in a vertical direction. The braid angle between the threads is determined by the ratio between the bobbins' angular speed and the take-up speed. The braid angle can be calculated with the radius of mandrel 'r' (cm), take-up speed 'V' (cm/s), and angular velocity of bobbins 'ω' $(rad/s)$. Moreover, the braiding angle is calculated by using the below-mentioned Equation 1 (C. Li et al., 2017; Potluri et al., 2003).

$$\tan\theta = \frac{r\omega}{V} \qquad \ldots (1)$$

Recent studies highlight the increasing relevance of braided textile architectures in advanced composite and lightweight structural applications. Experimental investigations show that parameters such as braiding angle, yarn hybridisation, and multilayer configurations strongly influence tensile strength, deformation behaviour, and energy absorption in tubular braided structures (Ghamkhar & Bodaghi, 2024). In addition, multidirectional 3D braided composites demonstrate superior structural integrity and damage tolerance compared with conventional laminated composites, with performance governed by fibre orientation and interfacial interactions (Dang et al., 2025; Mishra, 2023). These developments support the growing adoption of fibre-reinforced braided structures in lightweight engineering

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applications (Hassan & Saeed, 2024). Gautam et al. reported that bi-axial braided composites exhibit pseudo-ductile tensile behaviour, whereas tri-axial braids with axial fibre inserts show a sudden load drop after peak strength due to axial tow failure. They also observed that increasing braid angle reduces axial strength, modulus, and specific energy absorption while increasing strain to failure (Gautam et al., 2021). Yang et al. developed a scalable and systematic geometric model for cross-scale modelling of braided structures using a novel matrix transformation framework (Yang et al., 2025).

This review article presents a comprehensive and critical review of braided structures, with special emphasis on the geometric aspects of braids, the systems of materials used in braiding, the braiding techniques used in the production of braids, and the structural properties of braids in a wide variety of engineering applications. By integrating the recent advances in braid architecture, fibre reinforcement techniques, and advanced braiding techniques such as three-dimensional braiding and automatic braiding machines, the study reveals the key parameters controlling the process–property relationships in braided materials. The results of the present review article will help to understand the properties of braids. These findings are particularly relevant in today's braided-structure industries, where escalating needs for lightweight, high-strength, and multifunctional materials are driving technological advancements. In addition, the research analysis presented in this review article identifies the current research gaps and opportunities that could open the door for the development of the next generation of braided composite and textile materials for aerospace, automotive, and protective applications.

## 2 | HISTORY OF BRAIDING

Braiding has been a crucial process in transforming fibres into more useful forms throughout history. It is considered one of the earliest textile processes, dating back over 17,000 years. Ancient civilisations braided smaller, natural-fibre strands to create stronger structures like ropes. Handmade braids have a rich history, with evidence dating back to 8600-5780 BC from Peruvian burial sites, where they were used in ropes, looped bags, and twined fabrics. These braids predate woven fabrics due to their simplicity and functionality. Braided cord impressions have been found in pottery from the fourth millennium BC, and braided rugs were made worldwide long before the time of Christ. Braids were used functionally and decoratively in Egyptian, Huari, Chavin, and Japanese cultures, with the oldest being flat braids. The Japanese art of silk braiding, known as "kumihimo," dates back to 8000 BC, initially created by hand and later using braiding apparatuses by 645-784 AD. Kumihimo was significant in war, used to lace armor, and is still used for sword handles, obi belts, and hair adornments, with specific patterns indicating societal rank. Records from ancient China and Japan indicate that braiding was practised before 4000 BC. Historically, braiding involved the oblique interlacing of three or more strands. The first braiding machine existed before the Industrial Revolution; braids are described as fabrics where threads intersect diagonally. Sling braids, used as weapons to hurl projectiles, were prominent in Incan and Peruvian cultures and also found in Africa, India, Tibet, and the Far East, and were used until the seventeenth century. These braids featured intricate patterns and sometimes incorporated an inner core braid for more complex designs. Other historical braiding practices include hair plaiting, maypole dancing, and looped braids found in medieval Finnish and Swedish churches.

The invention of the braiding machine is attributed to Thomas Walford, who patented a braiding machine in 1748. After Walford, the German Bockmuhl introduced a simple braiding machine in 1767, later modified by the Frenchman Perrault. By the mid-1900s, braiding machines transitioned from wooden to iron structures, credited to Johan Heinrich Bockmuhl. The demand for braids to cover electrical wires led to faster machinery. A significant advancement was the Japanese Naiki-dai, a wooden machine developed in the mid-19th century, combining Kumihimo table braiding and industrial maypole machines. Despite its complexity, it remains manual in operation. In the late 1940s, mandrel-based technology emerged, renewing interest in braiding composite materials on maypole machines. In 1964, Bluck introduced the "Bias Weaving" machine, leading to innovations in producing complex shapes for various applications. Over the next 20+ years, many modifications were made, including two-step, four-step, and five-step processes (Alagirusamy & Padaki, 2015; Bicking, 2011). In recent times, the braiding process has experienced transformational changes, transitioning from a traditional interlacing approach to a highly regulated, digitally enhanced manufacturing system. One of the most notable advancements is the incorporation of Computer Numerical Control (CNC) technology into current braiding machinery. These systems enable automated management of important factors such as carrier motion yarn tension, and take-up speed, allowing for exact braid angle modifications and seamless transitioning between patterns such as biaxial and triaxial configurations. Furthermore, 3D braiding technology has significantly

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increased the structural value of braided textiles. Unlike standard two-dimensional braids, 3D braiding allows for the creation of solid, multilayered preforms with reinforcement in three directions, resulting in higher interlaminar strength and dimensional stability. These 3D braids are now widely employed in the aerospace, automotive, and healthcare industries, particularly for turbine components, composite I-beams, and ortho prosthesis. Advanced braided systems currently use high-performance fibres like carbon, aramid, and UHMWPE, and the incorporation of bio-based materials like PLA and silk has broadened braiding uses in sustainable medical devices and surgical sutures (Bilisik, 2013, 2020; Kamiya et al., 2000; Sontag et al., 2015).

Furthermore, digital simulation techniques like finite element modelling and digital twins have become indispensable tools for braid design and optimisation. These tools enable researchers and engineers to mimic braid behaviour under a variety of loading circumstances, optimise structural qualities, and lower prototype costs (Enders & Hobbach, 2019; Polini & Corrado, 2020; Saha et al., 2025a). These advancements show that current braiding is not only highly technologically sophisticated but also adaptable, with far-reaching implications for future textile manufacturing and composite design.

## 3 | METHODOLOGY

The literature data analysed in this study were collected from peer-reviewed research articles available through major scientific databases, including PubMed, Elsevier (ScienceDirect), MDPI, SpringerLink, Wiley Online Library, Taylor & Francis, and Google Scholar. This multi-database approach enhances the transparency, reliability, and reproducibility of the literature-based analysis presented in this study. The methodological framework is shown in Figure 2 with the help of a clear flowchart.

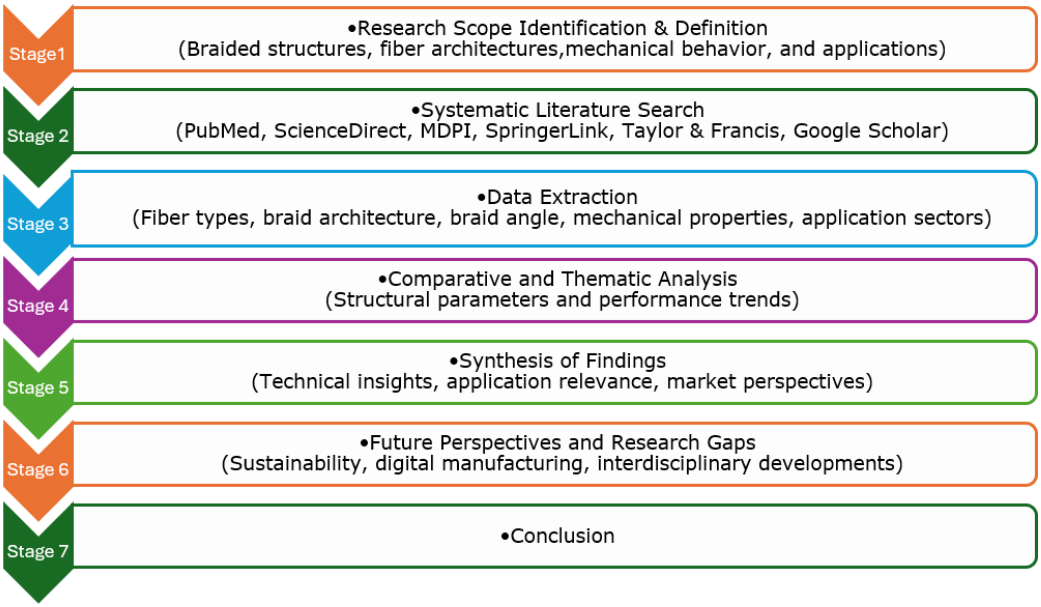



**Figure 2.** Methodological Framework for Literature Selection and Analysis (source: author's own work)

## 4 | GEOMETRIC PARAMETERS OF THE BRAID

The geometric characteristics of a braid are defined by the orientation of the constitutive yarns. The unit cell is the most important part of a braided structure. The architecture of a unit cell, dimensions, cell angle, and yarn orbit are highly influential on the structural properties of a braid. The layout of braid unit cells has a substantial impact on the structural and mechanical properties of 3D completely braided and 3D axial braided preforms manufactured using the four-step braiding method. Unit cell creation varies with braid patterns; odd-numbered rows produce fully linked structures, whereas even-numbered rows encourage interlayer connections mainly at the edges. The braid design also influences how tight the interlacing is within the unit cell (Bilisik, 2011b, 2016; Bilisik et al., 2015; Bilisik & Sahbaz, 2012). The 1×1 pattern creates a thin interweave, while 2×1 to 4×1 patterns produce coarser structures. Jamming, or the tightening or compression of yarns within the structure, is also an important consideration. Minimum jamming reduces unit cell width but increases density in the 3D preform, whereas maximum jamming results in a broader unit cell with a lower density. Axial yarn additions further alter the mechanical performance of braided preforms. The use of axial, filling, and Z-yarns increases tensile

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strength while decreasing the directional Poisson's ratio, resulting in better isotropy, notably in the transverse direction. The number of layers in the structure also influences yarn path shape. Increased layering lengthens the braider and surface yarns while shortening the edge and corner yarn paths; however, jamming has little effect on yarn length.

Furthermore, changes in braid designs somewhat modify yarn angles; in 3D braids, the surface angle rises while the braider angle falls from 1×1 to 3×1. The introduction of multilayer yarn routes at the unit cell border, as a result of additional layers, is critical for producing near-net-shape thick preforms for high-performance composite applications (Bilisik, 2011a, 2013; Bilisik et al., 2015a). The crimp and coverage factor are also two important parameters for defining a braid. Crimp (e) characterises the weaving of the yarn over the fabric's height. It is calculated as the percentage difference between the initial length of the yarn (L) and the length of the fabric (l): e = $\frac{L-l}{L}$ ×100. …..(2) (Brunnschweiler, 1954). Coverage factor (C) describes the ratio of the area covered by the yarns to the total area of the mandrel's surface (Guyader et al., 2013; C. Li et al., 2017).

### 4.1| Main Phenomenon During Braiding Process

The braiding process is influenced by several mechanisms affecting yarn positioning on the mandrel:

- *Friction in the Convergence Zone*: As yarns leave the carriers and interlace, friction reduces their rotational speed around the braiding axis, impacting the final braid parameters, such as the braiding angle.
- *Process Parameter Variation*: Changes in the platform's rotational speed and the mandrel's translation speed alter the position of the braiding front, creating a transitory stage before a steady-state run. This relative movement of the yarns on the mandrel can modify the braiding angle.
- *Tensile Force and Yarn Stretching*: During braiding, the yarns are stretched, and the tensile force causes the yarns to slide on the mandrel, altering their orientation (Du & Popper, 1994; Guyader et al., 2013; Rawal et al., 2012, 2015).

## 5 | TYPES OF BRAIDING AND BRAIDED STRUCTURES

The detailed classification of braided structures has been depicted in Figure 3.

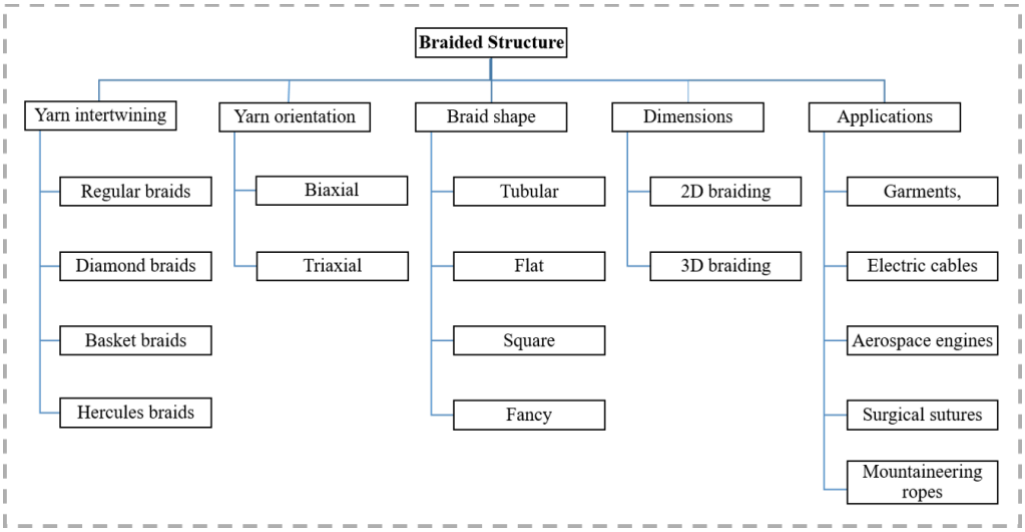



**Figure 3.** Classification of different braided structure (source: author's own work)

### 5.1| Yarn Intertwining

*Regular braids* featured 2/2 patterns of yarns intertwining, similar to the 2/2 twill woven fabric structure; *diamond braids* involved 1/1 yarn intertwining, resulting in a structure similar to plain woven fabric. The simulated images of 1/1 and 2/2 braided structures are shown in Figure 4. *Basket braids* comprised 2 × 2 structures, akin to a 2 × 2 box weave with two yarns crossing over and under each other. *Hercules braids* featured 3/3 yarn intertwining, similar to the 3/3 twill-woven fabric structure (Brunnschweiler, 1953).


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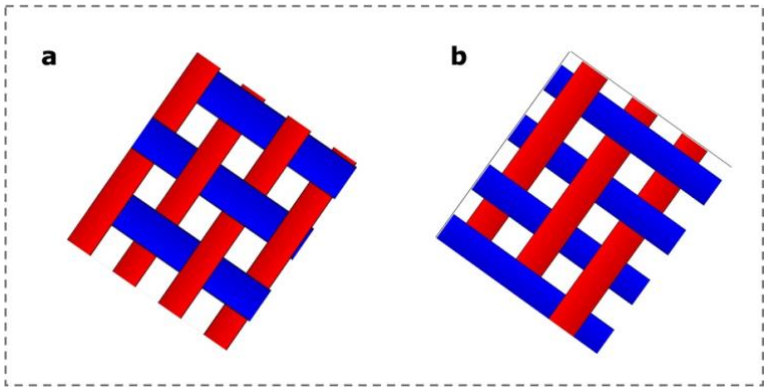



**Figure 4.** Different types of braided pattern (a) 1/1 braid pattern (b) 2/2 braid pattern (source: author's own work)

## 5.2| Yarn Orientation

*Biaxial braids* are created by intertwining two sets of yarns moving in opposite directions at an angle. *Triaxial braids are f*ormed by incorporating inlaid yarns along the machine or cross direction during braiding, resulting in a more complex structure (Alagirusamy & Padaki, 2015).

## 5.3| Braid Shape

*Tubular braids* consist of two groups of yarns spiralling in opposite directions, interlocking to form a circular path. Tubular braids form a helix structure, allowing them to conform to shapes and expand or contract. An even number of strands is required for a balanced braid, which can be made with or without a core for added rigidity (Brunnschweiler, 1953). In *Flat braids,* ribbon-like structures are formed by strands that follow a zig-zag path from side to side while interlacing with each other. Unlike tubular braids, flat braids reverse their direction at the edges, known as "terminals," forming a selvedge. While it is commonly believed that flat braids require an uneven number of strands (Alagirusamy & Padaki, 2015; Brunnschweiler, 1953). *The square braid* is a type of tubular braid where yarn groups spiral in opposite directions, interlacing with each other while maintaining a hollow centre (Bicking, 2011; Brunnschweiler, 1953; Kyosev, 2015). *Fancy braids,* also known as lace braids, refer to braids that deviate from simple flat or tubular constructions. They are characterised by irregular patterns or structures, offering a wide range of variations in terms of colour, interlacement type, and other aesthetic features. Traditionally used for garment and millinery trimmings, fancy braids have evolved with new fibres and technologies, allowing for more creative possibilities (Alagirusamy & Padaki, 2015; Bicking, 2011; Brunnschweiler, 1953; Kyosev, 2015).

## 5.4| Dimensions

Three-dimensional (3D) braids can be defined by the presence of through-thickness reinforcements, such as fibres in the through-thickness direction (Sontag et al., 2015). Three-dimensional braiding is very important in the development of complex fibre structures in a single process, making it very valuable for complex composite structures. Three-dimensional braiding technology has seen a resurgence in the 1960s to 1980s in the aerospace industry for the development of complex structures that are both stable and light, and further development in response to the increasing demand for damage-resistant and cost-effective structures in the 1990s. In the twenty-first century, the development of new fields such as nanotechnology and biotechnology has further increased the requirement for precision and customised manufacturing using 3D braiding technology (Emonts et al., 2021). Sophisticated computational algorithms were used in conjunction with CAD (computer-aided design) and CAM (computer-aided manufacturing) to regulate preform and composite operations. Unlike traditional two-dimensional braids like tubular and square braids, which are hollow, three-dimensional braids occupy three planes and can include yarns in the thickness direction, enhancing their strength and structural integrity. This method involves intertwining multiple yarn systems at right angles and can be classified by the process used, such as four-step Cartesian braiding, two-step and rotary 3D braiding or by geometric structure, such as rectangular, orthogonal & tubular. The process allows for precise control over each yarn end and offers benefits like compact machine size, low development costs, and flexibility in structure design (Bicking, 2011; Bogdanovich, 2016; Kamble & Behera, 2022; W. Li et al., 1990a, 1990b; Pastore & Ko, 1990; Wang et al., 2017). The 3D hexagonal braiding variant further maximises bobbin density via specialised

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horn gears and lace-inspired switches, ideal for fine materials in medical applications like stents. Table 1 outlines the comparative analysis of 2D and 3D braided structures.

**Table 1.** Comparative Analysis of 2D and 3D Braided Textile Preform Types (source: author's own work)

| Sr. No. | Braided Fabric Structures | Key Properties | Specific Applications |
|---|---|---|---|
| 1 | 2D-Biaxial Braided Fabric | Good in-plane stiffness and strength. It has low cost and light but its load transfer is limited under uniaxial/biaxial loads. | Cables, ropes, and hoses. They do also have marine lines as well as decorative with protective uses |
| 2 | 2D-Triaxial Braided Fabric | Improved off-axis performance, better dimensional stability, and reduced yarn slippage | Pipes, body structures, and parts for auto interiors |
| 3 | 3D-Biaxial Braided Fabric | High strength in-plane coupled with out-of-plane, good damage tolerance, strong bonding across layers, minimal slippage, high structural integrity | Engine components, as well as beams, including structural cores, and automotive pillars. |
| 4 | 3D-Triaxial Braided Fabric | Bonds with great strength between layers and suits impact resistance, plus structural integrity. | Chassis and also seat rails along with structural nodes as well as aircraft parts |
| 5 | 3D-Triaxial Braided Fabric by Over-Braiding | Stable Structure and damage-tolerant by over-braiding, improved formability, better fit for complex or tubular profiles. | Vehicle and aircraft interiors, as well as composite tubing materials. |
| 6 | Multiaxis-3D Braided Fabric | Balanced strength in all directions with low damage growth. Good formability, including outstanding drapability and dimensional accuracy. | Aerospace as well as missile parts, turbine parts, and those nose cones. |

Sources: (Bilisik et al., 2015a; Bilisik et al., 2015b; Bilisik, 2020; Bogdanovich, 2016; Sontag et al., 2015)

## 6 | TYPES OF FIBRES WIDELY USED IN BRAIDING

### 6.1| Natural Fibres

The employment of natural fibres like cotton, flax, jute, and silk can provide the advantages of biodegradability, low density, and cost-effectiveness. However, the usage of these types of fibres in braided composite materials for load-carrying applications is restricted by factors like higher moisture absorption, varying tensile properties, poor bonding at the fibre-matrix interface, and decreased long-term life. Empirical studies have consistently demonstrated that although braided composite materials based on natural fibres can provide reasonable tensile properties, their fatigue and creep properties are not satisfactory compared to synthetic fibre braids. In addition, the hydrophilic characteristics of these materials cause instability in dimensions in humid environments (Cicala et al., 2010).

### 6.2| Synthetic Fibres

Synthetic fibres, which include polyester, nylon, and polypropylene, are dominant in commercial braiding in terms of their mechanical properties, abrasion resistance, stability, and cost-effectiveness. Braids made of polyester exhibit dimensional stability and moderate tensile strength, whereas braids made of nylon exhibit enhanced toughness and impact resistance. However, creep deformation under constant loads is also a drawback of these materials, particularly for structural applications. Additionally, braids made of polypropylene exhibit poor thermal resistance and stiffness due to their low weight. However, it is found that most of these synthetic fibers are petroleum-based and are non-biodegradable, which poses environmental issues. Therefore, despite their dominance in braiding, these materials' environmental implications emphasise the need for further developments in materials technology.

### 6.3| High-Performance Fibres

Carbon, aramid (Kevlar), glass, and ultra-high molecular weight polyethylene (UHMWPE) fibres find extensive application in the development of advanced braided composites that include automotive parts,

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battery separators, ropes, and belts due to the superior properties offered by these materials, including high modulus and stiffness, toughness, superior impact resistance, corrosion resistance, and an exceptionally high strength-to-weight ratio. It has not been possible to find any single high-performance fibre meets the mechanical, thermal, and durability demands of the end user. As such, recent studies show the emergence of hybrid braided composites that include carbon-aramid, glass-carbon, and natural-synthetic fibre braids. These braids have the purpose of improving damage tolerance, enhancing the impact resistance and cost-effectiveness of the braided composite, and minimising the prospects of catastrophic failure. For example, carbon-aramid braided composites have shown superior residual strengths after impact compared to carbon braids alone (Cho & Park, 2021; Fong et al., 2025; Heitkamp et al., 2022). The detailed physical properties and application areas of natural fibres and Synthetic fibers used in braiding have been shown in Table 2 and Table 3, respectively.

**Table 2.** Details of Natural fibers used in braiding (source: author's own work)

| Fiber | Density (g/cc) | Tensile strength (Mpa) | Application area |
|---|---|---|---|
| Cotton | 1.55 | 300-700 | Ropes, sutures, belts |
| Silk | 1.34 | 500-750 | Sutures |
| Bamboo | 1.50 | 575-700 | Braided composites |
| Flax | 1.45 | 500-900 | Structural components of automobile |
| Hemp | 1.40 | 310-700 | Structural components of automobile |
| Jute | 1.45 | 450-550 | Ropes, composites |
| Sisal | 1.45 | 580-610 | Braided composites |

Sources: (Cicala et al., 2010; Torgal & Jalali, 2011)

**Table 3.** Details of Synthetic fibers used in braiding (source: author's own work)

| Fiber | Density (g/cc) | Tensile strength (Mpa) | Application area |
|---|---|---|---|
| Nylon | 1.14 | 450-900 | Sutures, ropes, belts, Cables |
| Polyester | 1.38 | 600-1000 | Sutures, battery separator, Cables |
| Polypropylene | 0.91 | 318-675 | Sutures, ropes, hoses, Cables |
| Polyglycolic acid | 1.50 | 750-900 | Sutures, meshes, scaffolds |
| Carbon | 1.80 | 3500-5000 | Drive shafts, structural panels, tubes |
| E glass | 2.6 | 1700-2700 | Drive shafts, joints, and connectors |
| Aramid | 1.45 | 2900-4000 | Ropes, hoses, structural components |
| Steel | 7.8 | 750-1000 | Sutures, structural components |
| Aluminium | 2.7 | 250-400 | Aircraft propeller, air fan blade case |

Sources: (Hearle, 2001; Mckenna et al., 2000; Wallenberger, 2000; Wallenberger et al., 2001; Weli, 1990)

## 6.4| Application of braids

Braided fabrics find extensive applications across various sectors, including textile, civil infrastructure, aerospace, medical, transportation, and electrical fields and some examples are shown in Figure 5.

- *Textile and Garment Applications:* Braids are used for cords, laces in clothes and shoes, candlewicks, sash cords, and ropes for activities like mountaineering, yachting, and parachuting (Wotton, 2001).
- *Technical Textiles:* Important applications include mountaineering ropes with kernmantle structures for strength, low stretch, durability, and abrasion resistance.
- *Sporting Goods:* Braided reinforcements are used in baseball bats, hockey sticks, nets, golf clubs, etc., for their strength and flexibility.
- *Electrical and Transportation Applications:* Braided structures are used in electrical insulation, cables, truck winch ropes, automobile front-end aprons, and energy storage flywheels for hybrid electric vehicles (Bilisik et al., 2015a; Faust et al., 1988; Fung & Hardcastle, 2001; Khoshravan & Paykani, 2012; Ko, 2008; Linden & Reddy, 1995).
- *Aerospace:* Applications include aircraft engine parts and one-piece aircraft horizontal stabilisers due to their high strength, lightweight, and stiffness (Johnston et al., 2017).
- *Civil Infrastructure:* Braided structures are used in trenchless pipes, metallic ropes for elevator lifting, bridge ropes, cement reinforcement, and inflatable helicopter repair shelters (GangaRao et al., 2006; Karbhari, 1998; Nanni et al., 1993; Waldron, 2004; Yilmaz & Tercan, 2021).
- *Medical:* Medical applications include prosthetic limbs, stents, sutures, biodegradable implants, bone plates, surgical cables, biomedical tubing, artificial ligaments, tendons, cartilage, and

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catheters (Barber et al., 2013; Chang et al., 2020; Cooper et al., 2005; Cruz et al., 2014; Indelicato et al., 1989; Kothari, 2008; Lu et al., 2005; Magnussen et al., 2011; Nambi Gowri & King, 2023; Nutton et al., 1999; Osborne et al., 1984; Seitz et al., 1998; Siedhoff et al., 2011).

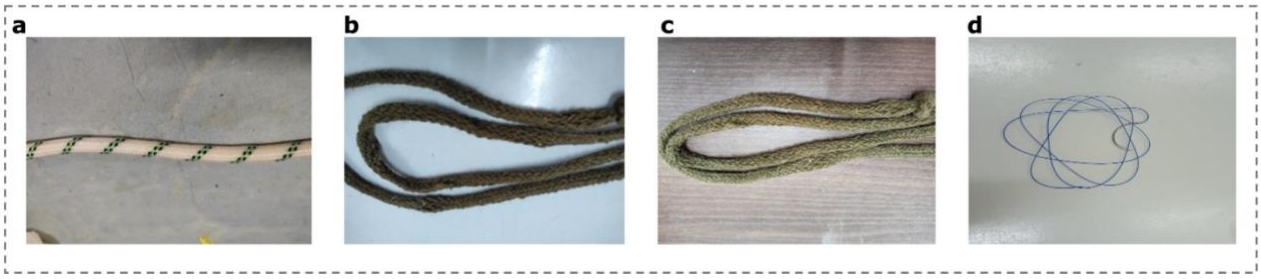



**Figure 5.** Different examples of braided structures (a) Mountain ropes, (b) Geo-meshes (c) Braided ropes and (d) Surgical sutures (source: author's own work)

## 7 | DETAILS OF TOP-LISTED BRAIDING COMPANIES IN THE WORLD

Table 4 lists renowned braiding companies with their country of origin, establishment year, and broad areas of application.

**Table 4.** Top-listed Braiding companies in the world (source: author's own work)

| Company name and Country | Established year | Application area | References |
|---|---|---|---|
| **A&P Technology**, USA | 1817 | Braided biaxial sleevings, biaxial, triaxial fabrics and tapes. | (A & P tech, 2024) |
| **Herzog** Oldenberg, Germany | 1861 | Floating lines. Ropes and net yarns for fishing, Shoelaces. cords and climbing ropes for yachting. | (Herzog, 2024) |
| **Lamb Knitting** Massachusetts | 1867 | Cords, shoelaces, trimmings, stents, wires. | (Lamb, 2024) |
| **Mayer & Cie** Albstadt, Germany | 1905 | Hose, lace, cords, cable shielding, servicing of different machine parts | (Mayer & Cie, 2024) |
| **Wardwell** High Street, USA | 1911 | Hose, lace, cords, cable shielding, medical catheters, fishing line, elastic cords. | (Wardwell, 2024) |
| **Ratera** Barcelona, Spain | 1942 | Elastic ropes, Solid braids, Medical sutures, Fishing nets, cords, sleeves, covers, sailing ropes | (Ratera, 2024) |
| **O.M.A** Vimercate, Italy | 1953 | manufacturer of braiding machinery, parts, and bobbin winders, vertical and horizontal maypole braiding machinery | (OMA, 2015) |
| **Geesons International** India | 1966 | Ropes, wires, harness, jute braids, ceramic, packing, fiberglass braiding | (Geesons, 2023) |
| **Hsiang Chuan Machinery** Changhwa, Taiwan | 1970 | Textile cords, Isolating Sleeves, Sports and safety, Tubes and Hoses, Stainless Steel Hoses | (Hsiangchuan, 2024) |
| **ETK-lesmo** Milano, Italy | 1970 | Construction of braiding machines. Surgical threads, climbing ropes, Electrical cable shielding, Steel cable extrusion | (Lesmo, 2018) |
| **Cobra braiding** England | 1981 | Harness, cable assemblies, wire, medical sutures | (Cobra Braids, 2021) |
| **Penguin Engineers** India | 1991 | Hose, wire, yarn braider | (Penguin Engineers, 2021) |

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| | | | |
|---|---|---|---|
| **Steeger usa,** Inman, USA | 2005 | Medical sutures, catheters, wire, cables, harnesses, composites | (Steeger usa, 2024) |
| **TapeFormers ltd,** UK | 2005 | Hose, cables, tapes | (Tapeformers, 2024) |

## 8 | MERITS AND DEMERITS OF BRAIDING

Braiding offers several advantages over conventional fabric formation techniques, including cost-effectiveness, excellent strength in all directions, and the ability to fabricate complex shapes efficiently. Modern advancements in braiding equipment have facilitated the automatic fabrication of various braided structures, overcoming issues such as braid convergence, processing costs, time, and stability (Chou & Ko, 1989; Gopalkrishnan, 2007). However, braiding does have limitations that include the need to move the entire supply of braiding yarns, large machine size relative to the braidable cross-sectional size of preforms, limitations on the length of braids that can be formed, constraints on fibre architecture options, and the requirement for different machines to vary braiding patterns. In Table 5, the comparison of different types of fabric formation techniques is shown.

**Table 5.** Comparison of Fabric Formation Techniques (source: author's own work)

| Parameters | Weaving | Knitting | Nonwoven | Braiding |
|---|---|---|---|---|
| Need of yarn | Two sets | One set | Not specific | Two sets |
| Direction of yarn | Warp: 0° Weft: 90° | Warp: 0° Weft: 90° | Randomly arranged | Towards machine direction |
| Fabric formation process | Interlacing | Interlooping | Interlocking (thermal, mechanical, chemically) | Intertwining |
| In-plane Shear resistance under uniaxial stress | High at bias direction (45°), low at machine and cross direction | Low in all directions | High in all directions | High at machine (0°) and bias direction (45°), low at cross direction (90°) |
| Produce complex shapes | Possible | Not possible | Possible | Highly possible |
| Dimensional stability | High | low | Moderate | high |

Source: (Alagirusamy & Padaki, 2015; Chou & Ko, 1989; Gopalkrishnan, 2007)

## 9 | CURRENT MARKET INSIGHTS

The global hair braiding market is projected to grow at a CAGR of 3% from 2023 to 2032. In 2022, the market size was valued at USD 529.3 million and is expected to reach USD 625.3 million by 2032. The hair braiding market encompasses the industry and segment dedicated to the practice of braiding or plaiting hair, which involves interweaving or twisting strands to create various intricate and decorative patterns. The braiding equipment market was valued at USD 655.14 million in 2023 and is expected to reach USD 854.56 million by 2030, growing at a CAGR of 3.53% from 2024 to 2030. This market focuses on the creation, production, and sale of equipment and accessories designed for the braiding process, which involves interlacing strands or threads to form a strong and flexible structure (Verified Market Reports, 2024). The valuation is anticipated to reach USD 5.5 billion (Markets and Markets, 2024). Braided composites market size is projected to reach USD 484.66 million by 2027 from USD 347.9 million in 2020, at a CAGR of 4.85% during the forecast period (Maximize Market Research, 2023). In addition to the above, it can be said that the highest market revenue comes from the textile and sporting sector, followed by the medical, automotive, aerospace, and electrical industries. In the case of the region, the highest growth comes from North America and decreases for Europe, Asia Pacific, and Africa. Therefore, most available market data are derived from proprietary industry analyses based on survey-based estimations, manufacturer-reported production capacities, and forecasting through compound annual growth rate (CAGR) assumptions.

### 9.1| Market evolution and Technological barriers

The international market for braided composites is influenced by the market trends observed in the fields of lightweight mobility devices, aerospace fuel efficiency, the expansion of electric vehicles,

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biomedical devices, and sustainability regulations. However, there are certain barriers that must be overcome, such as the initial investment required in equipment, the complexity involved in the modelling of the process, and the lack of standardisation. Technological advancements such as the implementation of CNC control in 3D braiding, the level of automation, and the implementation of hybrid fibre systems have been helping to overcome these barriers. This holistic approach has revealed that the prospects of the development of braided composites depend on the concurrent development of the related fields of material innovation, automation, and design optimisation (Hossain et al., 2024).

### 9.2| Application–Market Integration: A Technical Perspective

The industrial adoption of braided structures is not driven solely by material strength but by the interaction between architectural mechanics, manufacturability, and sector-specific performance requirements. Across industries, braid geometry, fibre type, and processing economics collectively determine market viability (Research, 2025; P & S Intelligence, 2025). In aerospace structures, damage tolerance and weight reduction are the primary concerns. Braided composites are found to be more advantageous than laminated composites because of the reinforcement in the through-thickness direction. Although the fabrication cost of braided composites is higher than laminates, the advantage in near-net-shape forming and structural reliability makes them suitable for engine parts, reinforcements in the airframe, and structural members. In the automotive sector, tubular and biaxial braiding is used in drive shafts and torsional members because it distributes shear loading better than filament winding. Glass and carbon-glass braids are often the best choice because of their cost and stiffness benefits. In biomedical applications, the flexibility of braided structures is a crucial factor. The ability to modify the braiding angle allows for radial stiffness as well as axial compliance to be controlled, as in stents and ligament substitutes. Natural fibres, such as silk, are being used, despite having a lower mechanical performance compared to synthetic fibres, because of the trend toward improved biofunctional properties. In the Renewable Energy sector, braided composite materials are gaining more attention as a potential solution for reinforcing wind turbine blades, as well as retrofitting civil structures with cable systems. The corrosion resistance requirements, along with durability, make glass- and carbon-fibre braided composite materials suitable candidates. In consideration of the rising global investment in renewable energy, braided reinforcement materials are likely to experience a steady increase in demand (Trivedi, 2025).

## 10 | CONCLUSION AND FUTURE STUDIES

This review highlights the significant progress in braided textile structures, emphasising the influence of braid architecture, fibre selection, and structural parameters on the mechanical and functional performance of braided materials. The analysis demonstrates that braided structures offer key advantages such as continuous fibre reinforcement, multidirectional load-bearing capability, and the ability to produce complex near-net-shape components, making them highly suitable for advanced engineering applications. Recent developments in automated and three-dimensional braiding technologies have further expanded their use across aerospace, automotive, biomedical, and technical textile sectors. Market trends further indicate sustained industrial interest driven by the growing demand for lightweight, high-performance, and durable composite materials. Despite these advances, challenges remain in predictive modelling, process optimisation, and sustainable material integration. The integration of advanced materials, digital manufacturing, and intelligent design frameworks will further unlock the transformative potential of braided structures in next-generation engineering and technical textile applications.

### 10.1| Research Gaps & Future Perspectives

Despite significant advancements in braiding technology and its expanding industrial applications, several research gaps remain, such as: 1) limited multiscale modelling and predictive simulation, 2) incomplete process–structure–property correlation, 3) limited research on smart and functional braided systems, 4) sustainability and circular economy challenges, and 5) optimisation of hybrid and 3d braided architectures. Now, to overcome these gaps, the braiding technology may be shaped by three converging imperatives: sustainability, digitalisation, and multifuncionality.

*Sustainability* will redefine material selection and processing strategies. Future braided systems must integrate recyclable thermoplastic matrices, bio-derived fibres, and life-cycle-driven design frameworks. Hybrid architectures combining natural and high-performance fibres may offer transitional solutions.

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*Digitalisation* will transform braiding from a mechanically controlled process to an intelligent manufacturing platform. Real-time yarn tension monitoring, AI-assisted parameter optimisation, and digital twin modelling of braid architecture will enable predictive design and process reliability. Integrating multiscale simulation with automated 3D braiding systems can reduce prototyping cycles and improve structural precision. Thirdly, braided structures are poised to evolve from passive reinforcements to multifunctional systems. The incorporation of conductive yarns, sensing elements, and adaptive materials opens pathways toward smart biomedical devices. Such advancements require interdisciplinary convergence across textile engineering, materials science, data analytics, and applied mechanics. Critically, a unified process–structure–property–performance framework is necessary to systematically link architecture design with mechanical reliability, manufacturability, and lifecycle performance. Finally, the strategic value of braided structures lies in their architectural adaptability. As industries demand materials that are lighter, tougher, smarter, and more sustainable, braided systems are uniquely positioned to meet these multi-objective requirements and emerge as a foundational technology for next-generation engineered structures.

## DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

## CONFLICT OF INTEREST STATEMENT

The author declares no conflict of interest.

## DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the author(s) used Quilbolt in order to reword some statements. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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## REFERENCES

A & P Tech. (2024). *A & P Technology*. Braider.Com. https://braider.com/braided-fabrics/ (accessed on 16 July 2024)

Alagirusamy, R., & Padaki, N. V. (2015). Introduction to Braiding. In S. Rana & R. Fangueiro (Eds.), *Braided structures and composites: production, properties, mechanics, and technical applications* (p. 1). CRC Press, Taylor & Francis Group. https://doi.org/10.1201/b18787

Barber, J. G., Handorf, A. M., Allee, T. J., & Li, W. J. (2013). Braided nanofibrous scaffold for tendon and ligament tissue engineering. *Tissue Engineering Part A: Research Advances*, *19*(11–12), 1265–1274. https://doi.org/10.1089/ten.tea.2010.0538

Bicking, A. (2011). *Explorations in fancy braid creation through the use of industrial machinery* [North Carolina State University, Raleigh, USA, 1-129]. http://www.lib.ncsu.edu/resolver/1840.16/6736

Bicking, A., & Oxenham, W. (2012). Variables and methods for aesthetic braid design. *Journal of Textile and Apparel, Technology and Management*, *7*(4), 1–17.

Bilisik, K. (2011a). Multiaxis Three Dimensional (3D) Woven Fabric. In *Advances in Modern Woven Fabrics Technology*, *May*. InTech. https://doi.org/10.5772/16530

Bilisik, K. (2011b). Three-dimensional axial braided preforms: Experimental determination of effects of structure-process parameters on unit cell. *Textile Research Journal*, *81*(20), 2095–2116. https://doi.org/10.1177/0040517511414978

Bilisik, K. (2013). Three-dimensional braiding for composites: A review. *Textile Research Journal*, *83*(13), 1414–1436. https://doi.org/10.1177/0040517512450766

Bilisik, K. (2016). Cartesian 3D braiding. In *Advances in Braiding Technology*. Elsevier Ltd. https://doi.org/10.1016/b978-0-08-100407-4.00004-1

Bilisik, K. (2020). Braiding and Recent Developments. In A. Patnaik & S. Patnaik (Eds.), *Fibres to Smart Textiles: Advances in Manufacturing, Technologies, and Applications* (pp. 131–152). CRC Press, Taylor and Francis Group, London, New York. https://doi.org/10.1201/9780429446511

Bilisik, K., Karaduman, N., & Bilisik, N. (2015a). Applications of Braided Structures in Transportation. In R. Fangueiro & S. Rana (Eds.), *Braided Structures and Composite* (Issue August, pp. 255–295). Taylor & Francis Group.

Bilisik, K., Nesrin, K., & Bilisik, N. E. (2015b). Fibre Architectures for Composite Applications. In: Rana, S., Fangueiro, R. (eds) Fibrous and Textile Materials for Composite Applications. Textile Science and Clothing Technology. Springer, Singapore. https://doi.org/10.1007/978-981-10-0234-2_3
Bilisik, K., & Sahbaz, N. (2012). Structure-unit cell-based approach on three-dimensional representative braided preforms from four-step braiding: Experimental determination of effects of structure-process parameters on predetermined yarn path. *Textile Research Journal*, *82*(3), 220–241. https://doi.org/10.1177/0040517511404597
Bogdanovich, A. (2016). An overview of three-dimensional braiding technologies. 1 - An overview of three-dimensional braiding technologies. In Y. Kyosev (Ed.), *Advances in Braiding Technology* (pp. 3–78). Woodhead Publishing. https://doi.org/10.1016/B978-0-08-100407-4.00001-6
Brunnschweiler, D. (1953). Braids and braiding. *Journal of the Textile Institute Proceedings*, *44*(9), P666–P686. https://doi.org/10.1080/19447015308687874
Brunnschweiler, D. (1954). The structure and tensile properties of braids. *Journal of the Textile Institute Transactions*, *45*(1), T55–T77. https://doi.org/10.1080/19447025408662631
Chang, C., Ginn, B., Livingston, N. K., Yao, Z., Slavin, B., King, M. W., Chung, S., & Mao, H. Q. (2020). Medical Fibers and Biotextiles. In *Biomaterials Science: An Introduction to Materials in Medicine* (Fourth Edi). Elsevier. https://doi.org/10.1016/B978-0-12-816137-1.00038-6
Chellamani, K. P., Sudharsan, J., & Sathish, J. (2013). Medical textiles using Braiding Technology. *Journal of Academia and Industrial Research (JAIR)*, *2*(1), 21–26.
Cho, J., & Park, J. (2021). Hybrid fiber-reinforced composite with carbon, glass, basalt, and para-aramid fibers for light use applications. *Materials Research Express*, *8*(12), 125304. https://doi.org/10.1088/2053-1591/ac406f
Chou, T., & Ko, F. K. (1989). *Textile Structural Composites*. Elsevier.
Cicala, G., Cristaldi, G., Recca, G., & Latteri, A. (2010). Composites Based on Natural Fibre Fabrics. In P. D. Dubrovski (Ed.), *Woven Fabric Engineering* (pp. 317–342). Intech open, Europe. https://doi.org/10.5772/10465
Cobra Braids. (2021). *Cobra braiding machinery*. https://www.cobrabraids.com/ (accessed on 16 July 2024)
Cooper, J. A., Lu, H. H., Ko, F. K., Freeman, J. W., & Laurencin, C. T. (2005). Fiber-based tissue-engineered scaffold for ligament replacement: Design considerations and in vitro evaluation. *Biomaterials*, *26*(13), 1523–1532. https://doi.org/10.1016/j.biomaterials.2004.05.014
Cruz, J., Rana, S., Fangueiro, R., & Guedes, R. (2014). Designing artificial anterior cruciate ligaments based on novel fibrous structures. *Fibers and Polymers*, *15*(1), 181–186. https://doi.org/10.1007/s12221-014-0181-4
Dang, B., Tang, J., & Shang, Y. (2025). Shear Failure Analysis of 3D Seven-Directional Braided Composites. *Coatings*, *15*(223), 1–18. https://doi.org/10.3390/coatings15020223
Du, G. W., & Popper, P. (1994). Analysis of a circular braiding process for complex shapes. *Journal of the Textile Institute*, *85*(3), 316–337. https://doi.org/10.1080/00405009408631277
Emonts, C., Grigat, N., Merkord, F., Vollbrecht, B., Idrissi, A., Sackmann, J., & Gries, T. (2021). Innovation in 3D Braiding Technology and Its Applications. *Textiles*, *1*(2), 185–205. https://doi.org/10.3390/textiles1020009
Enders, M. R., & Hobbach, N. (2019). Dimensions of digital twin applications - A literature review. *25th Americas Conference on Information Systems, AMCIS 2019*, *April*.
Faust, H., Hogan, E., & Margasahayam, R. (1988). Development of an Integral Composite Drive shaft and coupling. *National Technical Specialist"s Meeting on Advanced Structures*, 10.
Fong, A., Wong, D. H., Lau, S., Debnath, S., Anwar, M., Davies, I. J., & Johar, M. Bin. (2025). A review on the hybrid polymer composites comprising natural fi bre and nanomaterial reinforcement. *Journal of Composite Materials*, *59*(22), 2615–2646. https://doi.org/10.1177/00219983251334861
Fung, W., & Hardcastle, M. (2001). Textiles in automotive engineering. In *Textiles in automotive engineering*. https://doi.org/10.1533/9781855738973
GangaRao, H. V. S., Taly, N., & Vijay, P. V. (Eds.). (2006). *Reinforced Concrete Design with FRP Composites*. CRC Press.
Gautam. M., Sivakumar. S., Barnett. A., Barbour. S., Ogin. S L., Potluri. P. (2021). On the behaviour of flattened tubular Bi-axial and Tri-axial braided composites in tension. *Composite Structures,* 261(113325), 1-10. https://doi.org/10.1016/j.compstruct.2020.113325
Geesons. (2023). *Geesons International Braid Machines*. Geesons.Com. http://www.geesons.com/ (accessed on 16 July 2024)
Ghamkhar, G., & Bodaghi, M. (2024). Biaxial tubular hybrid braided structures with supreme tensile performance: Experimental and statistical assessments. *Construction and Building Materials*, *453*(November), 139059. https://doi.org/10.1016/j.conbuildmat.2024.139059
Gopalkrishnan, D. (2007). *Braiding and narrow width fabrics*. Fibre 2 Fashion. https://www.technicaltextile.net/articles/printarticle/2668 (assessed on 17 August 2023)
Guyader, G., Gabor, A., & Hamelin, P. (2013). Analysis of 2D and 3D circular braiding processes: Modeling the interaction between the process parameters and the pre-form architecture. *Mechanism and Machine Theory*, *69*, 90–104. https://doi.org/10.1016/j.mechmachtheory.2013.04.015
Hamouda, T., Aly, N. M., & Elshakankery, M. H. (2020). An experimental study on the interaction between braiding structural parameters and their effects on ropes mechanical properties. *Journal*

*of Industrial Textiles*, 1–27. https://doi.org/10.1177/1528083720960732
Hassan, H. Z., & Saeed, N. M. (2024). Advancements and applications of lightweight structures : a comprehensive review. *Discover Civil Engineering*. 1 (47). https://doi.org/10.1007/s44290-024-00049-z
Hearle, J. W. S. (2001). High-performance fibres. In J. W. S. Hearle (Ed.), *Woodhead Publishing*.
Heitkamp, T., Girnth, S., Kuschmitz, S., Klawitter, G., Waldt, N., & Vietor, T. (2022). Continuous Fiber-Reinforced Material Extrusion with Hybrid Composites of Carbon and Aramid Fibers. *Applied Sciences*, 12(17), 8830. https://doi.org/10.3390/app12178830
Herzog. (2024). *Herzog braiding and Winding Machines*. Herzog-Online.Com. https://herzog-online.com/braidingmachines/ (accessed on 16 July 2024)
Hossain, T., Shahid, A., Mortuza, G., Hossain, I., & Mahmud, Nadim. (2024). Techniques, applications, and challenges in textiles for a sustainable future. *Journal of Open Innovation: Technology, Market, and Complexity*, *10*(1), 100230. https://doi.org/10.1016/j.joitmc.2024.100230
Hsiangchuan. (2024). *Hsiang Chuan Machinery*. Www.Globalbraid.Com. https://www.globalbraid.com/ (accessed on 16 July 2024)
Indelicato, P. A., Pascale, M. S., & Huegel, M. O. (1989). Early experience with the GORE-TEX polytetrafluoroethylene anterior cruciate ligament prosthesis. *The American Journal of Sports Medicine*, *17*(1), 55–62. https://doi.org/10.1177/036354658901700109
Johnston, J. P., Pereira, J. M., Ruggeri, C. R., & Roberts, G. D. (2017). High speed thermal imaging on ballistic impart of triaxially braided composites. *32nd Technical Conference of the American Society for Composites 2017*, *2*, 1346–1360. https://doi.org/10.12783/asc2017/15273
Kamble, Z., & Behera, B. K. (2022). A novel geometric model of four-directional 3D braided preforms. *Journal of Industrial Textiles*, *51*(10), 1701–1715. https://doi.org/10.1177/1528083720918856
Kamiya, R., Cheeseman, B. A., Popper, P., & Chou, T. W. (2000). Some recent advances in the fabrication and design of three-dimensional textile preforms: A review. *Composites Science and Technology*, *60*(1), 33–47. https://doi.org/10.1016/S0266-3538(99)00093-7
Karbhari, V. M. (1998). Use of composite materials in civil infrastructure in Japan. In *International Technology Research Institute* (Issue August). Loyola College in Maryland. https://www.academia.edu/2178939/Use_of_composite_materials_in_civil_infrastructure_in_Japan%0Ahttp://wtec.org/pdf/compce.pdf
Khoshravan, M. R., & Paykani, A. (2012). Design of a composite drive shaft and its coupling for automotive application. *Journal of Applied Research and Technology*, *10*(6), 826–834. https://doi.org/10.22201/icat.16656423.2012.10.6.342
Ko, F. K. (2008). Textile composites for automotive structural components. *Textile Advances in the Automotive Industry*, 320–343. https://doi.org/10.1533/9781845695040.4.320
Kostar, T. D., & Chou, T. W. (1999). Braided structures. In A. Miravete (Ed.), *3-D textile reinforcements in composite materials* (p. 217). Woodhead Publishing Ltd. and CRC Press LLC, Cambridge, United Kingdom,217–240.
Kothari, V. K. (2008). Progress in Textiles: Science & Technology Vol 3. In *IAFL Publications* (Vol. 3). https://doi.org/10.1177/004051750107100216
Kyosev, Y. (2015). Braiding Technology for Textiles. In *Woodhead Publishing is an imprint of Elsevier*. http://www.kyosev.com/lib/exe/fetch.php?media=braiding_technology_for_textiles_table_of_content.pdf.
Lamb. (2024). *lamb kintting Machine Corporation*. Lambkmc.Com.
Lesmo, E. (2018). *ETK lesmo braiding machine*. Etksrl.It. https://etksrl.it/en (accessed on 16 July 2024)
Li, C., Wang, X., Zhao, F., Wang, F., Ting, Z., & Wang, L. (2017). Modeling of braiding parameter impact on pore size and porosity in a tubular braiding fabric. *E - Polymers (De Gruyter)*, *17*(3), 221–226. https://doi.org/10.1515/epoly-2016-0060
Li, W., Hammad, M., & El-Shiekh, A. (1990a). Structural analysis of 3-D braided preforms for composites part I: The four-step preforms. *Journal of the Textile Institute*, *81*(4), 491–514. https://doi.org/10.1080/00405009008658725
Li, W., Hammad, M., & El-Shiekh, A. (1990b). Structural analysis of 3-D braided preforms for composites part II: The two-step preforms. *Journal of the Textile Institute*, *81*(4), 515–537. https://doi.org/10.1080/00405009008658726
Linden, D., & Reddy, T. B. (1995). Handbook of Batteries. 3rd Edition, The McGraw-Hill Companies, Inc.
Lu, H. H., Cooper, J. A., Manuel, S., Freeman, J. W., Attawia, M. A., Ko, F. K., & Laurencin, C. T. (2005). Anterior cruciate ligament regeneration using braided biodegradable scaffolds: In vitro optimization studies. *Biomaterials*, *26*(23), 4805–4816. https://doi.org/10.1016/j.biomaterials.2004.11.050
Magnussen, R. A., Carey, J. L., & Spindler, K. P. (2011). Does autograft choice determine intermediate-term outcome of ACL reconstruction? *Knee Surgery, Sports Traumatology, Arthroscopy*, *19*(3), 462–472. https://doi.org/10.1007/s00167-010-1277-z
Markets and Markets. (2024). *Surgical Suture market size, share & trends by product, suturing device, suture thread, application, end user and region- global forecast to 2028*. https://www.marketsandmarkets.com/Market-Reports/surgical-sutures-market-18374832.html (accessed on 16 July 2024)
Masters, J. E., Naik, R. A., & Minguet, P. J. (1994). Effects of Preform Architecture Modulus and Strength of 2-D Triaxially Braided Textile Composites. *Mechanics of Textile Composites*

*Symposium*, 349–378.
Maximize Market Research. (2023). *Braided Composites Market – Global Industry Analysis and Forecast (2021-2027) – by Fiber Type, Architecture Type, Application and Region.* Available at: https://www.maximizemarketresearch.com/market-report/global-braided-composites-market/91379/#:~:text=Market Size in 2020%3A,US %24 59.95 Bn (accessed on 07-16-2024)
Mayer, & Cie. (2024). *mayer & cie braid machine.pdf*. Www.Mayercie.Com. https://www.mayercie.com/en/ (accessed on 16 July 2024)
Mckenna, H. A., Hearle, J. W. S., & Ohear, N. (2000). *Handbook of fibre rope technology* (H. A. Mckenna, J. W. S. Hearle, & N. Ohear (Eds.)). Woodhead Publishing Limited,England.
Mikhailov, P. (1993). New Textile Materials development, production, application. In J. Buckley (Ed.), *Fiber-Tex 1992, The Sixth conference on Advanced Engineering Fibers and Textile Structures for Composites* (pp. 125–138). NASA Conference Publication, Washington DC.
Mishra, R. (2023). *Advances in Textile Structural Composites*. *Polymers*. 15(4): 808 https://doi.org/10.3390/polym15040808
Nambi Gowri, K., & King, M. W. (2023). A Review of Barbed Sutures—Evolution, Applications and Clinical Significance. *Bioengineering*, *10*(4), 1–19. https://doi.org/10.3390/bioengineering10040419
Nanni, A., Okamoto, T., Tanigaki, M., & Osakada, S. (1993). Tensile properties of braided FRP rods for concrete reinforcement. *Cement and Concrete Composites*, *15*(3), 121–129. https://doi.org/10.1016/0958-9465(93)90001-P
Nutton, R. W., Mclean, I., & Melville, E. (1999). Tendons allografts in knee ligament surgery. *Journal of the Royal College of Surgeons of Edinburgh*, *44*(4), 236–240.
OMA. (2015). *OmA High Tech System*. Www.Omabraid.It. https://www.omabraid.it/en/ (accessed on 16 July 2024)
Omeroglu, S. (2006). The effect of braiding parameters on the mechanical properties of braided ropes. *Fibres and Textiles in Eastern Europe*, *14*(4), 53–57.
Osborne, A. H., Telfer, R. C., & Farquharson-Roberts, M. A. (1984). Recent experience with carbon fibre. *Journal of the Royal Naval Medical Service*, *70*(2), 66–69.
Pastore, C. M., & Ko, F. K. (1990). Modelling of textile structural composites part I: Processing-science model for three-dimensional braiding. *Journal of the Textile Institute*, *81*(4), 480–490. https://doi.org/10.1080/00405009008658724
Pei, L., Xiao, Z., Geng, L., Wu, J., Zhang, F., & Sun, Y. (2019). Surface parameters measurement for braided composite preform based on gray projection. *Journal of Engineered Fibers and Fabrics*, *14*, 1–16. https://doi.org/10.1177/1558925019887621
Penguin Engineers. (2021). *Heavy duty wire braider*. Www.Penguin.In. https://www.penguin.in/hydraulic-hose/wirebraid.html (accessed on 16 July 2024)
Polini, W., & Corrado, A. (2020). Digital twin of composite assembly manufacturing process. *International Journal of Production Research*, *58*(17), 5238–5252. https://doi.org/10.1080/00207543.2020.1714091
Potluri, P., Rawal, A., Rivaldi, M., & Porat, I. (2003). Geometrical modelling and control of a triaxial braiding machine for producing 3D preforms. *Composites Part A: Applied Science and Manufacturing*, *34*, 481–492. https://doi.org/10.1016/S1359-835X(03)00061-7
P. & S Intelligence. (2025). *Natural Fiber Composite Market Size & Opportunities Analysis - Growth Strategies, Competitiveness, and Forecasts (2025 - 2032)*. Prescient & Strategic Intelligence. https://www.psmarketresearch.com/market-analysis/natural-fiber-composite-market (accessed on 2026-03-02)
Ratera. (2024). *Ratera, Your Braiding Industry*. Ratera.Com. https://ratera.com/en/ (accessed on 16 July 2024)
Rawal, A., Kumar, R., & Saraswat, H. (2012). Tensile mechanics of braided sutures. *Textile Research Journal*, *82*(16), 1703–1710. https://doi.org/10.1177/0040517512445340
Rawal, A., Potluri, P., & Steele, C. (2005). Geometrical Modeling of the Yarn Paths in Three-Dimensional Braided Structures. *Journal of Industrial Textiles*, *35*(2), 115–135. https://doi.org/10.1177/1528083705057574
Rawal, A., Saraswat, H., & Sibal, A. (2015). Tensile response of braided structures: A review. *Textile Research Journal*, *85*(19), 2083–2096. https://doi.org/10.1177/0040517515576331
Research, G. (2025). *Braided Composites Market by Fiber Type, Braiding Technique, Manufacturing Process, End Use Industry, Resin Type - Global Forecast 2025-2032*. 360i Research. https://www.giiresearch.com/report/ires1870921-braided-composites-market-by-fiber-type-braiding.html (accessed on 2026-04-26)
Saha, R. N., Datta Roy, M., & Ghosh, S. (2025a). Developing Uniform Surgical Suture Size Between USP/EP and Textile Engineering Numbering System. *Indian Journal of Surgery*, *0123456789*. https://doi.org/10.1007/s12262-025-04300-4
Saha, R. N., Datta Roy, M., & Ghosh, S. (2025b). Effect of braiding parameters on physical properties of braided structure. *Indian Journal of Fibre & Textile Research*, 1–23.
Seitz, H., Marlovits, S., Schwendenwein, I., Müller, E., & Vécsei, V. (1998). Biocompatibility of polyethylene terephthalate (Trevira® hochfest) augmentation device in repair of the anterior cruciate ligament. *Biomaterials*, *19*(1–3), 189–196. https://doi.org/10.1016/S0142-9612(97)00201-9
Siedhoff, M. T., Yunker, A. C., & Steege, J. F. (2011). Decreased Incidence of Vaginal Cuff Dehiscence

after Laparoscopic Closure with Bidirectional Barbed Suture. *The Journal of Minimally Invasive Gynecology*, *18*(2), 218–223. https://doi.org/10.1016/j.jmig.2011.01.002
Sontag, T., Yang, H., Gries, T., & Ko, F. (2015). Recent advances in 3D braiding technology. *Advances in 3D Textiles*, 153–181. https://doi.org/10.1016/B978-1-78242-214-3.00007-3
Steeger usa. (2024). *Medical Braid Machines*. Steegerusa.Com. https://steegerusa.com/ (accessed on 16 July 2024)
Tapeformers. (2024). *Tapeformers Braid Machine*. Tapeformers.Com. https://tapeformers.com/about-us/ accessed on 16 July 2024
Torgal, F. P., & Jalali, S. (2011). Natural fiber reinforced concrete. In R. Fangueiro (Ed.), *Fibrous and composites materials for civil engineering applications* (pp. 154–167). Woodhead Publishing Limited.
Trivedi, P. (2025). *Renewable Energy Market Size, Share, Trends, Industry Analysis Report By Product (Solar Power, Hydropower, Bioenergy, Wind Power, Others), By Application, By Region – Market Forecast, 2025–2034*. Polaris Market Research. https://www.polarismarketresearch.com/industry-analysis/renewable-energy-market (accessed on 2026-03-02)
Verified Market Reports. (2024). *Global Braiding Equipment Market By Type (Vertical Braiders, Horizontal Braiders), By Application (Textile and Sporting, Industrial), By Geographic Scope and Forecast*. Www.Verifiedmarketreports.Com. https://www.verifiedmarketreports.com/product/braiding-equipment-market/ (accessed on 16 July 2024)
Waldron, P. (2004). The use of FRP as embedded reinforcement in concrete. In R. Seracino (Ed.), *FRP Composites in Civil Engineering—CiCE* (p. 342). Taylor & Francis Group.
Wallenberger, F. T. (2000). Structural Silicate and Silica Glass Fibers. In F. T. Wallenberger, R. Naslain, J. B. Macchesney, & H. D. Ackler (Eds.), *Advanced Inorganic Fibers, Materials Technology Series,* (Vol. 6, pp. 129–168). Springer, Boston, M A. https://doi.org/10.1007/978-1-4419-8722-8_6
Wallenberger, F. T., Watson, J., & Li, H. (2001). Glass Fibers. In D. Miracle & S. Donaldson (Eds.), *Composites Volume 21* (pp. 27–34). ASM International. https://doi.org/10.31399/asm.hb.v21.9781627081955
Wang, P., Legrand, X., & Soulat, D. (2017). Three-Dimentional Textile Preform Using Advanced Textile Technologies for Composite Manufacturing. *Textiles for Advanced Applications*. https://doi.org/10.5772/intechopen.68175
Wardwell. (2024). *Wardwell Braiding Co*. Wardwell.Com. https://www.wardwell.com/ accessed on 16 July 2024
Weli, E. D. (1990). Carbon Fibers. In J. B. Donnet, R. C. Bansal, & M. Dekker (Eds.), *Polymers for Advanced Technologies* (Vol. 3, p. 47). CRC Press, New York. https://doi.org/10.1002/pat.1992.220030109
Wotton, D. (2001). *The Application of Textiles in Rubber* (D. Wotton (Ed.)). Rapra Technology Limited. ISBN: 1-85957-277-4, https://epdf.pub/queue/the-application-of-textiles-in-rubber.html
Yang, N., Jiang, G., & Li, B. (2025). Matrix transformation framework for modeling and analyzing braided structures. *Journal of Engineered Fibers and Fabrics*, *20*, 1–17. https://doi.org/10.1177/15589250251399716
Yilmaz, F., & Tercan, M. (2021). Comparison of Structural and Physical Properties of PES Sheathed Pa and PES Double Braided Rope Lanyards Used in Working At Height. *Usak University Journal of Engineering Sciences*, *4*(1), 15–27. https://doi.org/10.47137/uujes.873977

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