Braiding: From Cordage to Composites

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Abstract: Braiding is one of the narrow width textile manufacturing methods. Apart from the use of braids in garment and shoes, braiding found its use in a wider area of technical textile applications such as rope and cable. In addition, braiding is a more suitable method for developing seamless cylindrical textile reinforcement for developing composite structures. Fast manufacturing process with a range of fibre angles and reduced wastage are key reasons for braiding to be used in composite industries. This article intends to provide a broader perspective of braiding technology by covering its history, process and its applications. Details of a braiding machine, process and structures were explained to provide a general background. Customary use of braided structures was reviewed as well as further discussions on the use of braiding process for composites materials.

Key Words: Braiding, Plait, Rope, Structural composite

1. Introduction

Braiding[1] is the method of producing a structure by the intertwining of three (Fig.1a) or more strands together. Several other definitions can be found in the literature[2] with the inclusion of shape, structure, application, the material used and so on. The principle of manufacturing though remains the same. Plait or plaiting is a widely known term which is a class of braid. Rope, line and cord are collectively known as cordage. Although the conventional use of braided structures was limited to textile articles, however, development of industrial braiding equipment expanded its use to manufacture braids for technical applications such as rope[3], cables, over-braided pipes, medical textiles, composites etc. Use of braiding methods for cordage, cables, and wires are the widely used conventional technical application of braiding process.

In order to reduce global emission of greenhouse gases, since the beginning of the 21st-century use of textile composite materials for engineering applications has been growing. Fibre reinforced polymer matrix composites became a popular lightweight alternative to metals due to its strength-to-weight ratio in industries such as aerospace and automotive. As the demand for faster manufacturing increased, development of textile reinforcement otherwise known as preform adopted conventional methods such as weaving and winding. However, the requirement for seamless cylindrical sleeve reinforcement with various fibre orientations created a new application area for braiding process.

This article explains fundamental principle of two-dimensional (2D) braiding and different types of machines. A brief history and traditional use of braided products in various fields of the application were discussed. An introduction to the use of braiding process for composite materials and its application has also been discussed towards the end of the article to address the importance of braiding process for the study of composite materials.

2. Historical Background

Braiding is one of the early inventions of mankind that appeared in the form of hair plaiting. Study on prehistoric textiles[4] differentiates braiding from weaving in terms of 'Oblique interlacing' with the elements not being parallel or at a right angle. Archaeological findings record earliest example of artificial cordage which is a fishing net produced about 10000 years ago[3]. Later in history, the uses of ropes were also reported in ancient Spain, Egypt and Assyria. The documents in China and Japan indicate the use of braiding in various forms and methods in 4000 BC[5].

Despite the early use of braid in the form of plait or rope, the manufacturing was predominantly by hand or using some hand tools[6]. Development of mechanical equipment for producing a braid structure is relatively recent, during the era of industrial revolution. The first braiding equipment patent titled *"An engine or machine for the laying or intermixing of Threads, Cords, or Thongs of different kinds, commonly called Platting"* was issued in Manchester, the UK in 1748[7]. Although the first iron-built machine was developed in Germany in 1767[5]. Since the early development of braiding machines, various braiding methods and mechanisms for were invented. The following sections describe the widely used maypole braiding machine and its principle.

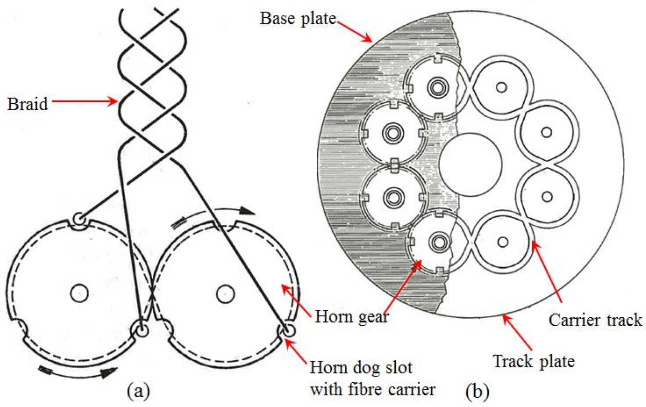

Fig. 1: Schematic of (a) a three thread braiding process (b) horn gear in between track and base plate in a tubular braider[8]

3. Braiding equipment

The oblique interlacement of fibres can be achieved by different mechanical means such as horn gear, track, circular rack and pinion with cam ring[8] etc. Typically braided structures are cylindrical produced in a circumferential or tubular braider. Also, there are equipment to develop structures with flat and complex cross sections. The two-dimensional braiding machines are either vertical or horizontal according to the orientation of the track plate. According to the fibre delivery system arrangement on the track, it can be either maypole (Fig. 2a) or radial (Fig. 2b).

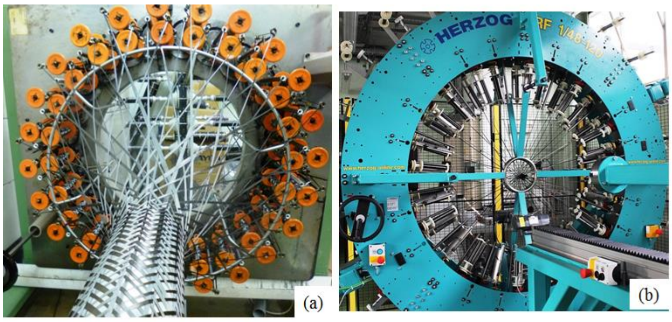

Fig. 2: 48-carrier braiding machines in the University of Manchester (a) maypole (Cobra Braiding Machinery Ltd) (b) radial braiding machine (August Herzog Maschinenfabrik GmbH & Co. KG)

Braiding machines usually have two major motions- rotating and linear. Rotating components braid a structure whereas linear motion acts as a 'take-up' or 'haul-off' process. The braid structure has fibre interlacement which is termed as 'intertwining' due to helical fibre passage. Most commercially available braiding machines use horn gear mechanism. The principle of intertwining is similar to that of 'maypole dance' and hence the process is known as maypole braiding.

A fundamental feature of the circumferential machines is the braid head or braider which includes at least bobbins with fibres, carriers with carrier driving mechanism and guide ring. A carrier (Fig.3) is an assembly of fibre guides, tension compensator mechanism and bobbin holder. A carrier is moved along a track by using 'horn gears' (Fig.1b) which are a combination of 'horn dogs' and 'spur gears'. The spur gears are placed below the horn dogs transmitting power to the mechanism. The bobbins with fibres are mounted on the two sets of counter-rotating carriers. Two adjacent carriers rotating in the same direction are placed in alternate slots of a 4 slot horn dogs which allow inter-gear transfer without any collision. These carriers follow serpentine paths (Fig.1b) on the track plate that changes the positions of the carriers. This change in a position eventually interlaces the fibres rotating in one direction with those rotating in opposite direction.

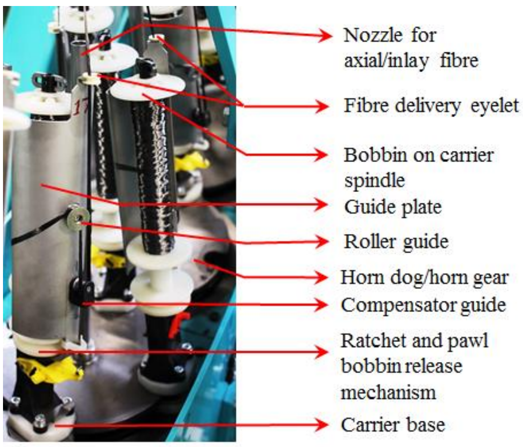

Fig. 3: Different components of a radial braider carrier

A take-up mechanism has multiple functions other than accumulating the produced braid. The speed of the take-up as well as the horn gear determines the fibre orientation of the braid structure. In order to over-braid another structure, it can be mounted on the take-up using clamping mechanism. During braiding as the take-up process pulls the braid away from the braider, the fibres from the delivery point of the carrier converge to the fell point. In this convergence zone, a guide ring is used between the fell-point and fibre delivery point. Various other types of braiding machines and guide rings have been discussed in detail by Kyosev Y.[9].Although using only 3 carriers simplest braid can be produced, the largest commercially available maypole braiding machine has 800 carriers[10].

The flat braiding machines also use horn gear principle. However, unlike circumferential braiders, instead of two individual intersecting tracks, the tracks are reversed at 'terminal gears'[8] (Fig.4a). Both flat and tubular braids are 2D braid structures. Profile or form braiding (Fig.4b) can produce various cross sections (square, rectangular, cruciform etc.) with solid braid structures. These structures are termed in the literature as 2.5D[9] since 3D braids can have considerably higher thickness. 3D braids can be produced using multi-step (two, four or six) processes. A broad classification of 3D braiding based on the interlacement and fibre axis was presented by Bilisik K.[11].

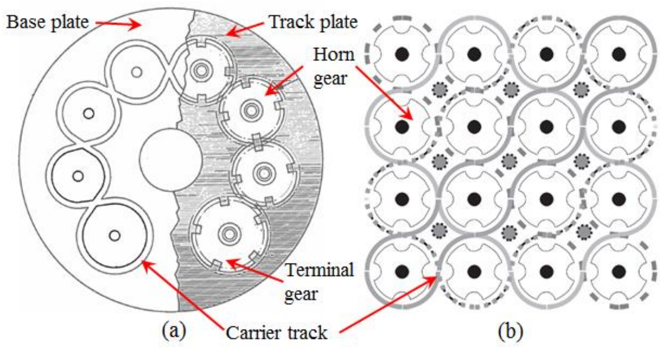

Fig. 4: Schematic of (a) flat braider carrier track[8] (b) profile (2.5D) braider with four tracks[9] also known as 4x4 braider

4. BRAID PARAMETERS

A tubular braid structure has the threads winding in a sinuous course while passing over one another creating interlacement. Hence the fibres in a tubular braid produce a set of interlacements as in woven structure, however, unlike woven structure the fibre path in a braid is helical. The fibre interlacement in a braid typically can be a diamond (1/1), regular (2/2) and Hercules (3/3). Other configurations such as 2/1, 3/1 and 3/2 can also be produced. The machine for producing a regular braid can also produce a diamond structure. However, for producing a Hercules braid, horn gears need to have 6 slots. Typically horn gears have 4 slots in a braiding machine to produce regular and diamond structures. Fibre orientation has significant effects on the mechanical properties of composite materials. An advantage of using a braid structure in composites is the wide range of fibre orientation compared to that of a woven structure with fibres at 0°/90° only. The fibre orientation in a braid with respect to the central axis of the structure is known as 'braid angle' (Fig.5a). It is a very important parameter as braid angle determines the mechanical properties of the braided product, especially for composites. The braid angle (α) can be predicted using equation 1[12]. Other important parameters for analysing braid structure and properties are cover factor[12], braid thickness, nesting factor[13] and fibre crimp angle.

$$\alpha = \frac{2\omega_h R_m}{N_h v} \quad (1)$$

In the above equation, ω_h, R_m, N_h and v indicates horn gear speed (rad/s), mandrel or core radius (mm), number of horn gears and take-up speed (mm/s).

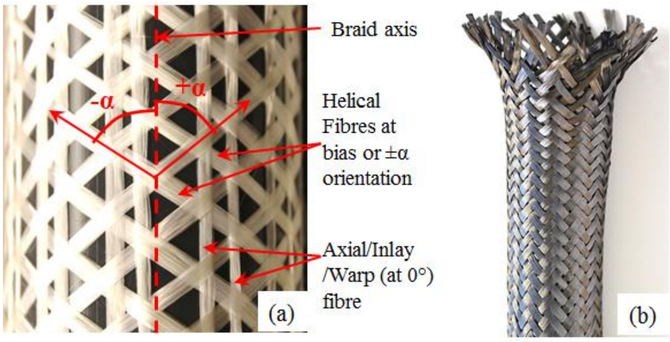

Fig. 5: (a) Glass fibres at different orientation in a braid with braid angle (±α) and braid axis which is same as the machine as well as longitudinal axis of the core (b) Carbon fibre braided sleeve

Considering the number of axes in which fibres are oriented in a braid, it can be classified as biaxial (Fig.5b) and triaxial braid (Fig.5a). In a triaxial braid, the axial (0°) fibres are placed in parallel to the braid axis and locate in between the interlacement of helical fibres. Biaxial braid fibres tend to 'scissor' and change angle while under tension when not braided over a core. As the angle changes, the diameter of braid also changes creating a 'Chinese finger trap'[14] effect. The principle can be used to influence multilayer braid thickness for composite manufacturing.

5. Conventional Applications of braid

Braided products are traditionally used for aesthetics as well as functional applications. In addition, braids in the form of ropes, have long been playing a major role in technical applications. Functional use can be classified based on not only aesthetic but also for a specific use. Whereas technical uses of braid are primarily in various technical textile areas. The fibres used for braiding varies depending on the application. Fibre types such as jute, rayon, polyester, nylon, polypropylene, acrylic, steel[5], sisal, Kevlar, Dyneema[6] etc. are used for braiding. Similar to other textile manufacturing such as weaving and knitting, in order to withstand the processing stress-strain, the fibres or threads used for braiding require protective coating or size.

A) Functional and aesthetic

Braided products are popular in textile application due to its seamless, narrow width and sometimes hollow structure. In addition, changing fibre type or colour can be done instantly by changing bobbins. This sudden changeover is less time consuming compared to a weaving process which requires different stages of preparation. Also, core material such as elastomeric yarns can be used for certain applications.

Braids used for decoration purpose (Fig.6a) in hats, ornamentation of uniform, rugs etc. are aesthetic. Flat braids are commonly used for embroidery[8]. Functional applications of braid are belt, drawstring (Fig.6b) with or without elastic core used in the seam of a garment or bag, shoe lace (Fig.6c), ribbons, candle wicks, carrying pendants, hanging baskets and so on.

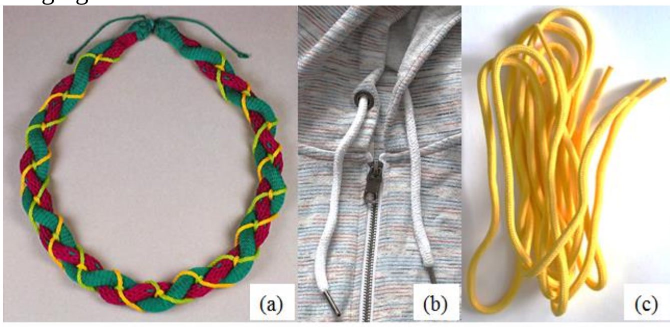

Fig.6 Examples of braided textile (a) Fancy (Versatile) braid[15] (b) drawstring for jacket (c) shoelace

B) Technical

Technical applications of braid span across a wide variety of industries. Tubular or solid core braids are often used for high-pressure hose, fishing line and net etc. Flat braids have application in industrial belts while square braids can be used as gasket[9]. Braiding is widely used for electrical power supply cable mainly to organise and manage the distribution of hundreds of meters of cables.

One of the major technical applications of braiding lies in the field of biomedical textiles. Examples of the use of braiding can be found in stents for implanting inside arteries[16], synthetic arteries[8], dental floss, artificial knee ligament[17], composite implant rod[18], prosthetic intervertebral disc etc.

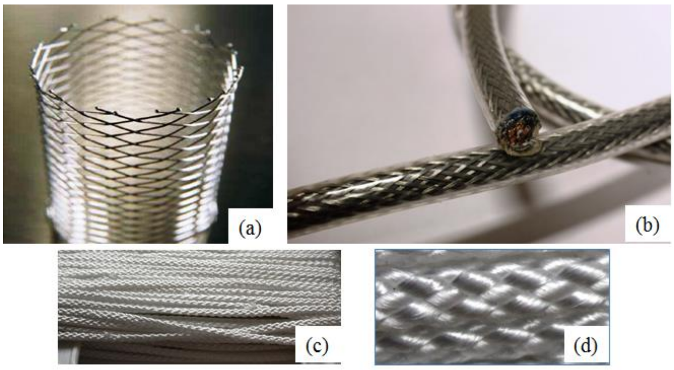

Fig.7: Technical braided products (a) stent[19] for biomedical use (b) electrical cable (c) rope (d) close view of rope

Due to its high load bearing capacity, braiding is also used for rope manufacturing. The uses of rope are broad and was classified mainly in four areas[3]- industrial, marine, recreation and general utility. Ropes are used for various sports activities such as mountaineering, skipping, skiing, yachting etc. Other uses of rope are mooring lines, bridge cables, elevators and heavy duty use in lifting, mining, winching, shipping and forestry[3] to name but a few.

6. Braiding for structural composites

Braided structural composites are mainly used in automotive, aerospace[20], marine and sports industries. Ko et al.[5] presented a chronological description of braided structures evolution in the field of composite materials. Potential of the braided preform as engineered materials specifically for using in composite structures was first explored by researchers in the aircraft company McDonnel Douglas[21]. Meanwhile, attention into braiding for composite manufacturing has increased due to the requirement of high production rate in manufacturing[20] as well as flexibility in fibre layup in different orientations.

In order to achieve required strength and stiffness of the material, textile reinforcement is manufactured using high-performance fibres such as glass, carbon and aramid. Due to its fibre orientation dependent behaviour, the composite material shows anisotropic properties. The preforms can be designed in a way so that their properties can be close to those of isotropic materials and such structures are known as 'Quasi-Isotropic' (QI). Three possible fibre orientations to achieve QI properties are ±45°/0°/90°, ±60°/0° and ±30°/90°. Braiding can produce a triaxial QI 0°/±60° layup, that can have the benefits significant reduction in labour cost, time as well as tooling cost[22] related to the cutting and placement of woven (0°/90°) fabrics to achieve ±45° orientation. Other than QI materials, some composites are designed to perform under certain loading conditions only. For example in an application such as drive shaft, torsional loading dominates and hence ±45° reinforcement is necessary. By wrapping woven fabrics (0°/90°) onto a tubular core, the composite tubular structure can be fabricated. However, to achieve desired ±45° orientation, it will require a diagonal layup which will eventually increase wastage. In contrast, braiding can produce a tubular ±45°/0 preform eliminating the manual fabric layup with little wastage. Composite mechanical properties can be tailored to the required properties as braid angle can range between ±10° to ± 85°[23] with fibres at 0°.

Braided composites are not only used for cylindrical structures, but also for complex shaped composites. A few examples[20] of braided composites are air duct, landing gear (Fig.8), structural columns, structures such as rocket launch tube, fuel pipes, pressure vessels, cable insulation[24], sports equipment such as bicycle frame, baseball bat, squash racquet and so on.

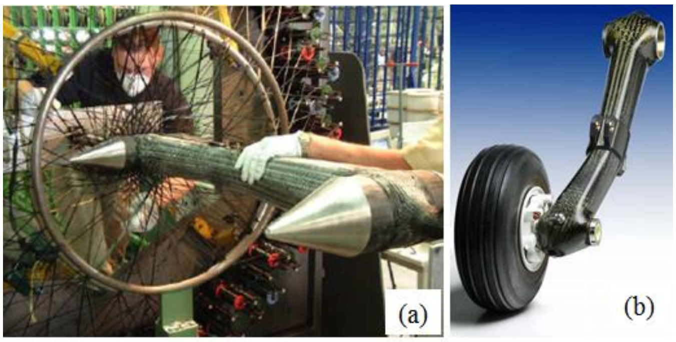

Fig. 8 (a) Over braiding of a trailing arm (b) braided composite helicopter landing gear[25]

7. CONCLUDING REMARKS

The ancient technology of braiding for manufacturing plait and ropes has been an advantageous process for many application areas. Despite the on-going modernization of the world, the use of rope is almost irreplaceable. Apart from this obvious application, braiding products are playing an important role in various medical textiles. The application of braided composites in the structural application is also growing. Studies on improvement of braiding machine, process and preforming remains an important topic for textile research.

REFERENCES

[1] P. Potluri, "Braiding," in *International Encyclopedia of Composites* vol. 1, L. Nicolais, A. Borzacchiello, and S. M. Lee, Eds., ed. New York: Wiley, June 2012.

[2] D. Brunnschweiler, "BRAIDS AND BRAIDING," *Journal of the Textile Institute Proceedings,* vol. 44, pp. P666-P686, 1953/09/01 1953.

[3] H. A. McKenna, J. W. S. Hearle, N. O'Hear, and T. Institute, *Handbook of Fibre Rope Technology*: Taylor & Francis, 2004.

[4] M. E. King, "Analytical Methods and Prehistoric Textiles," *American Antiquity,* vol. 43, pp. 89-96, 1978.

[5] F. K. Ko, C. M. Pastore, and A. A. Head, *Atkins & Pearce Handbook of Industrial Braiding*: Atkins & Pearce, 1989.

[6] B. Fronzaglia and N. E. Ropes, "The History of Rope," in *The Classic Yacht Symposium. Herrreshof Marine Museum*, 2006.

[7] T. Walford of Manchester (Lancashire) Chapman:, "Specification for "An engine or machine for the laying or intermixing of Threads, Cords, or Thongs of different kinds, commonly called Platting", Published Source: The sessional papers printed by order of the house of lords or presented by royal command in the session 1845, Vol XIII ", 15 March 1748.

[8] W. A. Douglass, *Braiding and braiding machinery*: Centrex Publishing Company; Cleaver-Hume Press Ltd., London, 1964.

[9] Y. Kyosev, *Braiding Technology for Textiles*. Amsterdam: Elsevier Science, 2014.

[10] M. Braley and M. Dingeldein, "Advancements in braided materials technology," in *46th International SAMPE Symposium and Exhibition*, Long Beach, Ca, 2001, pp. 2445-2454.

[11] K. Bilisik, "Three-dimensional braiding for composites: A review," *Textile Research Journal*, vol. 83, pp. 1414-1436, 2013.

[12] P. Potluri, A. Rawal, M. Rivaldi, and I. Porat, "Geometrical modelling and control of a triaxial braiding machine for producing 3D preforms," *Composites Part A: Applied Science and Manufacturing,* vol. 34, pp. 481-492, 2003.

[13] P. Potluri and T. V. Sagar, "Compaction modelling of textile preforms for composite structures," *Composite Structures,* vol. 86, pp. 177-185, 2008.

[14] S. S. Roy, W. Zou, and P. Potluri, "Influence of Braid Carrier Tension on Carbon Fibre Braided Preforms," in *Recent Developments in Braiding and Narrow Weaving*, Y. Kyosev, Ed., ed Cham: Springer International Publishing, 2016, pp. 91-102.

[15] B. J. Walker, "The Oh-So-Versatile Braid," in *Strands, Issue 22, The Braid Society*, ed, October 2015.

[16] S. Irsale, "Textile prosthesis for vascular applications " Doctoral dissertation, Auburn University, 2004.

[17] P. Potluri, W. D. Cooke, A. L. Lamia, and E. C. Ortega, "Designing carbon-polyester braids for ligaments," *Journal of Textile and Apparel, Technology and Management,* vol. 33, pp. 1-12, 2003.

[18] T. Hiermer, K. G. Schmitt-Thomas, and Z. G. Yang, "Mechanical properties and failure behaviour of cylindrical CFRP-implant-rods under torsion load," *Composites Part A: Applied Science and Manufacturing,* vol. 29, pp. 1453-1461, 1998.

[19] K. Chellamani, J. Sudharsan, and J. Sathish, "Medical textiles using braiding technology," *Journal of Academia and Industrial Research (JAIR),* vol. 2, pp. 21-26, 2013.

[20] C. Ayranci and J. Carey, "2D braided composites: a review for stiffness critical applications," *Composite Structures,* vol. 85, pp. 43-58, 2008.

[21] B. D. Haggard and D. E. Flinchbaughy, "Braided structures for launchers and rocket motor cases," *JANNAF S and MBS/CMCS subcommittee meeting, MDAC/Titusville,* November 1984.

[22] G. Wood, "Quasi-isotropic braid reduces cost in large composite tooling," *JEC Composites Magazine. Issue 53, Accessed: 11 Oct 2016,* 2009.

[23] P. Potluri and S. Nawaz, "14 - Developments in braided fabrics A2 - Gong, R.H," in *Specialist Yarn and Fabric Structures*, ed Oxford: Woodhead Publishing, 2011, pp. 333-353.

[24] S. S. Roy, P. Potluri, S. Canfer, and G. Ellwood, "Braiding ultrathin layer for insulation of superconducting Rutherford cables," *Journal of Industrial Textiles,* p. 1528083716661204, 2016.

[25] H. Thuis, "Composite landing gear components for aerospace applications," in *24th International Congress of the Aeronautical Sciences, Yokohama, Japan,* 2004.