Investigation of Braid Geometry for Complex Braided Composite Structures

A thesis submitted to the University of Manchester for the degree of Master of Philosophy in the Faculty of Science and Engineering

2018

Danjie Yang

SCHOOL OF MATERIALS
# Table of contents

1. Introduction.................................................................................................................. 17
   1.1. Introduction to the research topic................................................................. 17
   1.2. Research objective ......................................................................................... 19
   1.3. Outline of thesis............................................................................................ 20
2. Literature Review ........................................................................................................ 21
   2.1. Introduction to braiding ............................................................................... 21
   2.2. Braid machine components.......................................................................... 22
   2.3. Braid parameters .......................................................................................... 22
      2.3.1. Braid angle ............................................................................................ 23
      2.3.2. Unit cell ................................................................................................. 24
      2.3.3. Lay length ............................................................................................. 25
      2.3.4. Cover factor ........................................................................................ 26
      2.3.5. Crimp ..................................................................................................... 26
   2.4. Composite materials ...................................................................................... 28
      2.4.1. Application of composites ...................................................................... 28
      2.4.2. Braided composites .............................................................................. 29
      2.4.3. Application of braids and braided composites ....................................... 30
   2.5. Relation between mandrel position and compensation length during braiding.................................................................................................................. 31
      2.5.1. Introduction of compensation length ....................................................... 31
      2.5.2. Length from eyelet to braid ring .............................................................. 32
   2.6. Braiding using non-circular braid ring ......................................................... 33
   2.7. Wrinkle formation on braided preform ....................................................... 36
      2.7.1. Causes of wrinkle formation ................................................................. 37
      2.7.2. Wrinkle caused by bending ................................................................. 38
      2.7.3. Minimising wrinkles ............................................................................ 41
   2.8. Conclusions...................................................................................................... 42
6. Methods for Local Braid Angle Change

6.1. Introduction

6.2. Change in shape of braid ring

6.2.1. Braiding

6.2.2. Limitation of elliptical braid ring in maypole braider

6.3. Change in the position of the core

6.3.1. Relation between carrier compensation length and off-centre braiding

6.3.2. Limitation of off-centre braiding

6.3.3. Braiding with off-centre setting

6.3.4. Effect of core position on braid parameters

6.4. Conclusions

7. Analysis and Discussions

7.1. Effect of linear compression and linear tension on braided preforms

7.2. Effect of bending on braided preforms

7.3. Effect of shape of braid ring (elliptical braid ring)

7.4. Effect of off-centre setting of the braid ring

7.5. Wrinkle formation after resin infusion

7.6. Conclusions

8. Conclusions and Future Work

9. Bibliography
List of Figures

Figure 1 A composite sample with wrinkle analysed to observe the extent of out of plane deformation (a) Inner side of a bent braided composite tube with wall wrinkle generated during composite manufacturing. (b) Bent composite tube was cut along its length. (c) Details of wrinkle formation.

Figure 2 The angle $\alpha$ between yarn axis and braid axis is braid angle.

Figure 3 The braiding unit cell [15].

Figure 4 Tow path of lay length.

Figure 5 Side view of a braided textile illustrating measurements for crimp calculation notation [19].

Figure 6 Composite materials are used (a) throughout the body of Boeing 787 [24] and (b) Lamborghini car [25].

Figure 7 (a) Complex shapes are manufactured (b) RTM (Resin Transfer Molding) technology used to manufacture complex shaped braided composite [33].

Figure 8 Schematic of front view of bobbin carrier track (left) and side view of carriers (right) [34].

Figure 9 (a) Maypole braiding machine with an elliptical braiding ring. (b) Braiding angle changes with the changes on the radius of the creating ellipses [14].
Figure 10 Schematic diagram of the convergence zone between the elliptical ring and the fell point showing change in convergence length and fell point position due to the ellipticity of the ring .............................................. 34

Figure 11 Braiding using different braid ring [35].............................................. 35

Figure 12 Optical microscopic image showing a circumferential cross-section of the tube. The wrinkle amplitude is twice as much as the wall. [45]........... 36

Figure 13 Wrinkling due to shearing. Wrinkle appears after the locking angle achieved [49]......................................................................................... 37

Figure 14 Microphotographs of the cross section of samples with defect at the corner of the laminates (a) (b) wrinkles appeared on different materials (convex tool). (c) (d) wrinkles appeared on different materials (concave tool) ............................................................................................................ 39

Figure 15 Photographs of cross section of samples showing external wrinkle.. 39

Figure 16 Mechanics of the bending: analogy with a solid rod. The neutral axis moves toward outer surface of bend [52].................................................. 40

Figure 17 Weave Modifications to Remove Wrinkles (a) Normal fit. (b) Re-engineered fabric [56]................................................................. 42

Figure 18 Wrinkle appears on the metal after bending (a) side view (b) top view ............................................................................................................. 45

Figure 19 PVC tube used in this study........................................................... 46
Figure 20 Herzog USP 300. (a) Winding machine (b) fibre guide (c) bobbin (d) back view of the winding machine ................................................................. 47

Figure 21 The Cobra braiding machine during manufacture of a specimen ...... 48

Figure 22 Overbraided 180° bent tubular mandrel under vacuum along with additional vacuum bagging assembly ......................................................... 51

Figure 23 Cure cycle of epoxy resin (Araldite LY 564 and Aradur 2954) for composite manufacturing. The dotted line represents the uncontrolled cooling within the oven chamber ......................................................... 52

Figure 24 (a) Regular braid structure (b) Considering the braid unit cell acts as a trellis in which the intersecting four sides are pivoted [60] (c) unit cell schematic (d) unit cell schematic under compression assuming the sides are pivoted [61] ........................................................................................................ 55

Figure 25 Device used for linear compressing of braid. Blue arrows are compression forces ..................................................................................... 58

Figure 26 Images show the linear compression of a braid. The two ends of sleeve were folded instead of securing with cello tape which could apply a boundary condition and prevent free movement of fibre during compression ........................................................................................................ 59

Figure 27 Linear compression force applied on a braided sleeve. Initially braid angle is ±45°. The decrease in length leads to increase in braid angle and braid diameter after compression ......................................................... 61
Figure 28 Linear tension force applied on a braided sleeve. Initially braid angle is ±45°. The increase in length leads to braid angle and braid diameter decrease after compression.

Figure 29 (a) Braid angle measurement using digital protractor (b) Braid diameter measurement using digital calliper.

Figure 30 Relation between displacement and angle. Braid angle is ±45° when displacement is 0. Braid angle increases under compression and decreased under tension until it reaches to locking angle. The dotted red line when axial displacement is beyond 40 mm means the sleeve cannot be stretched any more.

Figure 31 Gap between interlaced fibre tow. Gap has an impact on diameter measurement using callipers.

Figure 32 Relation between displacement and diameter. Braid diameter increases or decreases under compression or tension respectively until braid angle reaches to locking angle.

Figure 33 Areal density increased with the increase of displacement.

Figure 34 Way of yarn spacing measurement.

Figure 35 Yarn spacing of the braid. Under linear compression and tension, yarn spacing decreased until braid angle reached to locking angle.

Figure 36 Schematic of a 90° bent tube [61].

Figure 37 (a) Top view of a carbon fibre braided core on bending equipment (b) Hydraulic bending equipment used for this study.
Figure 38 Cross-section of braided tube changed after bending. ‘Brazier effects’ could not be eliminated by filling the tube with sand but it was improved. Also it was verified that wet sand had better effect than dry sand........... 74

Figure 39 Bent tube. Tubes were bent to 90° and 180° respectively ...............75

Figure 40 Schematic of a 180° bent tube indicating different bending parameters [61]........................................................................................................76

Figure 41 Compression side, tension side and neutral sides at the curvature section after bending ........................................................................77

Figure 42 Braid angle formation after bending.............................................79

Figure 43 Schematic shows braid length change under compression of a multilayer braid................................................................................80

Figure 44 After bending a preform braided on a 25.4 mm diameter mandrel, at compression side, braid angle increased and reached to the highest angle at the centre of the curvature, and vice versa. The braid angle of double layers braids increased more rapidly than single layer braids at compression side but decreased slower than single layer braids. .......... 82

Figure 45 When a preform braided on a 12.7 mm diameter mandrel was bent, the change of braid angle was similar to 25.4 mm diameter mandrel bent. But braid angle changed more gradually from edges to the centre......... 83

Figure 46 Figure showing the maximum braid angle at compression side and minimum braid angle at tension side for a single layer braid after bending at 90° and 180°. The braid angles are collected from the centre of the
predicted braid angle were predicted by using equation 21 illustrated in Chapter 4.2 ............................................................................ 84

Figure 47 Image of elliptical braid ring ............................................................. 87

Figure 48 (a) Braid machine with elliptical braid ring (b) Schematic of a front view of the braiding machine (c) Two sets of braid angle were produced on four sides of the mandrel with the same angle in opposing sides .......... 89

Figure 49 Image of plate used for mandrel off-centre setting ......................... 92

Figure 50 Schematic of the front view of a braiding machine. Horizontal plane off-centre location of the mandrel is shown with respect to braid ring. Four measurement positions on the mandrel are shown in anti-clockwise direction ................................................................. 92

Figure 51 Schematic of circumferential braiding compensation length variation between braid ring and braid point. (left) side view. (right) top view ....... 93

Figure 52 Factors affecting the required compensation length during braiding. (a) Original setting is setting the distance between a braid ring and the eyelet to 100 mm with braid ring radius 100 mm and convergence length 110 mm. (b) (c) (d) When the mandrel was set 50 mm off-centre, the increase in the distance between braid ring and carrier eyelet, braid ring radius and convergence length (lower braid angle) resulted in more compensation length was required ................................................................. 95

Figure 53 Fibre loosed when mandrel was set 62.5 mm away from the machine centre ....................................................................................................................... 97
Figure 54 Effect of compensation limitation in braiding process. Mandrel was set 100 mm off-centre (a) front view of fibre slack (b) fibre slack during braiding (c) fibre hoop was created because of slack fibre tow (d) convergence length various due to fell point moving (e) fibre tow out of guide causing fibre damage ................................................................. 98

Figure 55 Comparing braid angle (maximum and minimum) before bending and after bending to 180° (12.5 mm offset). The dotted line indicates braid angle at the neutral axis ................................................................. 99

Figure 56 Change in braid angle (maximum and minimum) after bending (elliptical braid ring) ................................................................. 106

Figure 57 Half piece of composite tubes for observation of wall thickness (a) Wall thickness variation with small wrinkles are observed for composite, the preform of this composite was braided by using circular braid ring where the braid angle changed at the compression side to ±54° from ±45° at neutral axis. (b) Uniform wall thickness at compression side of the tube and the preform of this tube was braided by using elliptical braid ring where the angle changed to ±45° at compression side after bending from ±41° before bending ............................................................................. 109

Figure 58 Cross section of inner bent section. (a) Preform braided by using circular braid ring. (b) Preform braided by using elliptical braid ring..... 111
List of Tables

Table 1 Basic data for TORAYCA: T700SC 12000 60E [57] ......................... 44

Table 2 Outlines the details of tube braiding .................................................. 80

Table 3 Length change under compression on a multilayer braid ................. 81

Table 4 Braiding process parameters ............................................................... 88

Table 5 Braid angle are the same at opposing quadrants around the mandrel... 90

Table 6 Effect of convergence length on braid feasibility ............................. 91

Table 7 Data setting for off-centre braiding .................................................. 97

Table 8 Change of braid angle (°) after bending to 180° .............................. 101

Table 9 The maximum braid angle (°) at compression side after bending ...... 107

Table 10 The minimum braid angle at tension and the maximum braid angle at compression side after bending to 180° .................................................... 110

Table 11 Mean average thickness (mm) at tension and compression side after resin infusion .............................................................. 110
Abstract

The University of Manchester
Danjie Yang
Master of Philosophy
Investigation of Braid Geometry for Complex Braided Composite Structures
February 2018

The aims of this study are to investigate the mechanism of wrinkle formation on cylindrical preform during bending and minimise the wrinkle formation to improve the properties of the final products. It was found that changes in braid parameters due to the scissoring of fibre tows was one of the major influencing factors for causing out-of-plane deformation. In order to minimise or potentially eliminate this out of plane deformation that leads to wrinkle formation, the changes in braid angle and braid diameter under uniaxial tension and compression loading have been studied.

In this study, biaxial braid with ±45° braid angle was produced using T700 Toray carbon fibre tows on a circular cross-section cylindrical mandrel. Bending of the over-braided preform produced a significant change in braid angle around the circumference as well as along the length as a result of opposing forces (tensile and compressive) at the outer and inner of the bend. Optimisation of braid parameters was achieved by changing the braid angle locally around the circumference of the braid to compensate for distortion during the bending process.

Reducing the braid angle during braiding at the compression side of the mandrel can minimise the wrinkle formation during preforming using bending. Two methods were used to accomplish the change in braid angle in this study. One method was braiding using an elliptical braid ring instead of a circular braid ring. Two different braid angles were produced on the mandrel major and minor diameter of braid ring. The secondary method was braiding the mandrel/core off-centre of the braid ring. Different braid angles were achieved on the plane of off-set because of the difference in distance from braid ring to braid fell point. The braid angle measured after bending these braids and the change in braid angle were optimised due to changes in braid angle in the tension and compression sides as opposed to the angle along the neutral axis. This change eliminated one of the major factors that give out-of-plane deformation, resulting in wrinkles.

Braided structures that have been pre-formed to complex geometrical shapes were then resin infused to produce composites. Two preforms were braided using circular braid ring or an elliptical braid ring respectively. After bending and under pressure during resin infusion, optimised structures showed an improvement in wall thickness as well as wrinkle formation. Wrinkles were formed during resin infusion for the braid produced with a circular braid ring. The braid angle reduction in the preform stage resulted in the elimination of wrinkle formation. The optimised braid structure improved wall thickness of the composite.
Declaration

I declare that no portion of the work in the thesis has been submitted in support of another degree or qualification in this or any other university or another institute of learning.
Copyright Statement

i. The author of this thesis (including any appendices and/or schedules to this thesis) owns certain copyright or related rights in it (the “Copyright”) and s/he has given The University of Manchester certain rights to use such Copyright, including for administrative purposes.

ii. Copies of this thesis, either in full or in extracts and whether in hard or electronic copy, may be made only in accordance with the Copyright, Designs and Patents Act 1988 (as amended) and regulations issued under it or, where appropriate, in accordance with licensing agreements which the University has from time to time. This page must form part of any such copies made.

iii. The ownership of certain Copyright, patents, designs, trademarks and other intellectual property (the “Intellectual Property”) and any reproductions of copyright works in the thesis, for example graphs and tables (“Reproductions”), which may be described in this thesis, may not be owned by the author and may be owned by third parties. Such Intellectual Property and Reproductions cannot and must not be made available for use without the prior written permission of the owner(s) of the relevant Intellectual Property and/or Reproductions.

iv. Further information on the conditions under which disclosure, publication and commercialisation of this thesis, the Copyright and any Intellectual Property and/or Reproductions described in it may take place is available in the University IP Policy (see http://documents.manchester.ac.uk/DocuInfo.aspx?DocID=487), in any relevant Thesis restriction declarations deposited in the University Library, The University Library’s regulations (see http://www.manchester.ac.uk/library/aboutus/regulations) and in The University’s policy on Presentation of Theses.
Acknowledgement

I would like to take this opportunity to extend my sincere thanks to all the individuals and organisations for their kind support and help in the completion of this project. First and foremost, I would like to show my greatest appreciation to Prof Prasad Polturi who provided me with this opportunity to carry out this study. Also thanks for his valuable feedback, guidance and encouragement.

I would like to thank my academic advisor Dr Sree Shankhachur Roy who offered me invaluable assistance and support through the whole project duration. He explained knowledge in this subject area and analysis to me. Under his guidance, I managed to conduct the experimental work successfully. I also got a better understanding of the composite mechanism under his instructions.

I thank colleagues Dr Mayank Gautam, Kinjalkumar Patel and Lamis Jfairi for maintaining a friendly environment in the office. I thank Dr Vivek Koncherry, Dr Mohammad Islam, Hussein Dalfi and Roy Conway for everyday support that supports me spiritually. Also I thank Mr Thomas Kerr from weaving laboratory for his help.

I also wish to express my gratitude to the School of Materials at the University of Manchester for providing all the instruments and materials I needed to carry on my project research. The project went on well with their support.

Finally, I want to thank my parents and friends for their constant encouragement and support.
1. Introduction

1.1. Introduction to the research topic

Composites structures can sometimes have complex cross sections, rather than linear, with bending along the length. However, fibre orientation which is a significant parameter in determining the composite mechanical properties, can also change due to the change in shape [1]. Wrinkling is a serious defect that could potentially form during composite manufacturing due to such change in fibre orientation in bent sections (Figure 1) and it can lead to lower mechanical properties. In addition, if an over-braided preform is bent to a complex shape, fibre orientation can change as the fibres shear. This change in fibre orientation can influence wrinkle formation. This study will find out the relationship between fibre orientation and post-bending wrinkle formation. Two methods will be presented to minimize or even eliminate wrinkle formation.

One of the methods that will be attempted in order to minimise wrinkles is a change in fibre orientation (in case of a braid, the braid angle) circumferentially where bending forces a change braid angle. The rotational speed of carriers on the braiding machine and take-up speed of the core (mandrel) are the two main factors that can change the braid angle along the length of the mandrel (keeping the core diameter constant) [2].
Figure 1 A composite sample with wrinkle analysed to observe the extent of out of plane deformation (a) Inner side of a bent braided composite tube with wall wrinkle generated during composite manufacturing. (b) Bent composite tube was cut along its length. (c) Details of wrinkle formation

This change in braid angle is the same around the circumference of the mandrel as a braiding machine uses a circular braid ring or former which helps in braid formation. But braid angle cannot be changed around the circumferential directions with help of a circular braid ring. In this context, an elliptical braid ring can potentially achieve different braid angles circumferentially. Another method used in this study was mandrel off-centre setting to change the braid angle locally around the circumference direction.

CFRP (carbon fibre reinforced polymer) is formed of two components: polymer (often epoxy resin) as the matrix and carbon fibre as the reinforcement. CFRP can be expensive to produce [3] but is widely used in applications requiring high strength-
to-weight ratio and high rigidities, such as aerospace, automotive, civil engineering, sports goods and other technical applications. In structural composite applications performance can be affected by wrinkle formation. Vacuum bagging is a widely used technique for manufacturing CFRP composites. However, this technique can generate wrinkles when manufacturing braided composites. Vacuum bagging was used to apply mechanical pressure on the laminate in a consolidation process. When pressure is applied on the fibre preform, the thickness of the preform will reduce during a debulking process. In this case, with the total amount of fibres unchanged, the excess fibres are stacked to form wrinkles. This study used an elliptical braid ring and set the mandrel off-centre to achieve local braid angle changes and eliminate the unexpected wrinkle defects.

1.2. **Research objective**

The aim of this study is to optimise braided preforms for bent tubes containing region double curvature. The objectives of this research were categorized as follows.

- Study the change in the braid angle and minimise the angle distortion during bending.
- Investigate the mechanism of wrinkle formation during bending.
- Investigate methods to minimise wrinkle formation to improve the properties of final products.
1.3. Outline of thesis

Chapter 1 briefly introduces braiding and braided composites. Methods to mitigate wrinkle formation in bent braided composites were put forward.

In Chapter 2, a detailed review of literature in reference to braiding, braided composites, compensation length, braiding using non-circular braid ring and wrinkle formation is presented.

In Chapter 3 describes bobbin winding and braiding process. The process of manufacturing of composite by vacuum bagging was also covered in this chapter.

In Chapter 4, a detailed study of braid angle change under linear tension and compression was conducted due to its relevance with bending of braided preforms.

Chapter 5 describes the observations as the bending process was carried out. The braid angle increased under compression loading at the compression side and decreased at the tension side.

The Chapter 6 describes two methods to optimise the braid angle in the preform. One is using an elliptical braid ring instead of a circular braid ring for braiding. The other one is setting the mandrel off-centre to achieve local changes in the braid angle.

In Chapter 7, the results are shown with analysis. At the end of this chapter, the conclusions from the study are presented and recommendations for future research work are proposed.
2. Literature Review

A comprehensive review of literature with reference to the subjects of research is presented in this chapter. Firstly, some important braid parameters relevant to the study are introduced. Then an introduction to composite materials, composite manufacturing and the application of composites is given. This is followed by literature related to a technology of non-circular braid ring braiding. Finally, wrinkle formation in braided composites is investigated.

2.1. Introduction to braiding

Braiding is a textile method of producing a braid structure that was defined as “a process of interlacing three or more threads diagonally to the product axis (parallel to the longest dimension of the resulting product) in order to obtain a thicker, wider or strong product or in order to cover (over-braid) some profile” [4]. One of the earliest documented braid textile structures was produced in China over 4000 years ago [5]. The maypole braiding machine was inspired by the maypole dance, which was a conventional braiding machine that can produce tubular braided structures. Guyader et al. [6] illustrated the whole braiding process. In order to produce a braid, the horn gears are placed on the machine and the gears rotate with a constant angular velocity and the carriers move along the track path in two opposite directions. Thus, the interlacement of the yarns is deposited on the mandrel. Yarns are wound on bobbins placed on to the carriers. The yarn ends are fixed on the mandrel which is pulled through the braid ring by take-up mechanism in the centre of the whole machine.
The maypole braiding machine is inexpensive and can be run at high production speeds that makes it suitable for producing low-cost, high volume composites. Over-braiding a core is becoming popular in composite manufacturing. In this project, braiding of high performance carbon fibres will be carried out with the aim of developing composite.

2.2. Braid machine components

The maypole braiding machine consists of three primary components: a track plate, carriers, a braid ring and take-up device [7]. The yarns are wound on bobbins, which are mounted on carriers. The carriers drive horn gears move follow a track, which determines the carrier path and provides the resistance to the carrier to keep the track following the carrier in the horn dogs [2, 8]. Carriers are placed on horn gears, which usually have 4 slots. When a carrier reaches a track intersection, the driving force combined with shape of the track transfer the carriers from one horn gear to the next [9]. The take-up mechanism pulls the fibre tow out from a bobbin when a carrier rotates during braiding.

2.3. Braid parameters

The structural parameters can affect the braid geometry and performance. Braiding provides the primary features of composite reinforcement by laying fibres in many different ways. The process can vary the microgeometry of braid structure and produce varied parts [10]. The structural geometry of the braid is determined by many parameters, such as braid angle, convergence length and cover factor.
2.3.1. Braid angle

Braided composite has a feature that its mechanical properties can be changed by changing the fibre orientation, which is also called ‘braid angle’. The braid angle, which is the most important parameter in the braiding process, is made by the yarn with respect to the braid axis. To change the braid angle, either or both the take-off speed of the mandrel as well as the rotational speed should be changed. The braid angle ($\alpha$) can be calculated using the equation 1[2].

$$\alpha = \tan^{-1}\left(\frac{\omega R}{v}\right)$$

Where $\alpha$ is braid angle (between yarn axis and braid axis); $R$ is radius of cylindrical mandrel (cm); $v$ is take-up speed (cm/s); $\omega$ is average angular velocity of bobbins around the machine centre (rad/s).

Braid angle is related to rotation speed of horn gears around their own centre, the number of horn gears as well as take-up speed. The equation [2] is shown below.

![Figure 2 The angle $\alpha$ between yarn axis and braid axis is braid angle](image)

---

23
\[ \alpha = \tan^{-1}\left(\frac{2\omega_h R}{N_h v}\right) \] (2)

Where \( \omega_h \) is average angular velocity of the horn gears around their own centre (rad/s); \( N_h \) is number of horn gears

The longitudinal velocity of the mandrel and the angular rate of the spindle can be changed to change the braid angle on a cylindrical braided fabric. Fibre orientation is one significant parameter as it has an effect on mechanical properties [11, 12]. Lower braid angle leads to higher stiffness longitudinally, along the braid cylinder axis. Higher angle improves the radial strength [13]. However, change the longitudinal velocity of mandrel and rotation speed of the machine can only change the braid angle in axial directions. Nishimoto et al. [14] experimented to change the braid angle in circumference direction is that changing the form of braid ring to ellipse shape rather than a circle. It will be discussed in section 2.6.

2.3.2. Unit cell

The braid unit cell for the 2D braided architecture is shown in Figure 3. The overall volume of the braid unit cell is [15]:

\[ V = \frac{4Ha^2}{\sin 2\alpha} \] (3)

Where \( H \) = braid thickness; \( a \) = yarn spacing.
2.3.3. Lay length

Each yarn forms a helical path around a mandrel. The lay length, which is known as pitch length, is the longitudinal distance along the mandrel required for one complete helical wrap. Lay length is calculated using equation 4. Variation of lay length influences the final product performance due to its fibre orientation.

\[ L = \frac{\pi D}{\tan \alpha} \]  

(4)
2.3.4. Cover factor

In a review by Potluri et al. [2], it has been described that cover factor is the percentage of yarn covering the mandrel. It is the ratio of covered area over total area of the mandrel. Cover factor for a biaxial braid can be mathematically represented as:

\[
\text{CF} = 1 - \left(1 - \frac{W_y N_c}{4\pi R \cos \alpha}\right)^2
\]  

(5)

In this equation, \(W_y\) = yarn width; \(N_c\) = number of yarn carriers; \(R\) = effective mandrel radius; \(\alpha\) = braid angle

According to Zhang Q et al. [16] analysis, cover factor is related to braid angle and mandrel diameter. Increasing the braid angle or decrease the mandrel diameter can result in an increase in cover factor. Higher coverage occurs at particularly high or low angles. The minimum cover factor always occurs at a braid angle 45°.

2.3.5. Crimp

Crimp is defined [17] as "the waviness of a fibre" and is normally expressed numerically as either "the number of waves or crimps per unit length" or "the difference in distance between points on the fibre as it lies in a crimped condition and the same two points when the fibre is straightened under suitable tension". As the crimp reduces, the mechanical properties of composites reinforced with braid increased. But drape and in-plane permeability are generally decreased as the crimp decreases.

The Crimp (C), which is referred as the wave of a yarn in an interlaced structure, is a measure of the amplitude of the yarn in the 2D braided structure. The crimp is
calculated by the change in length of straightened yarns and the length of fabric. The equation is shown as [18]

\[ C = \frac{L - l}{l} \times 100\% \]  \hspace{1cm} (6)

Where \( C \) is crimp percentage; \( L \) is the length of straightened yarn before crimping; \( l \) is the length of fabric after crimping.

Figure 5 Side view of a braided textile illustrating measurements for crimp calculation notation [19]

This parameter may change due to factors that increase or decrease the length of yarn path. For example, change the diameter of the yarns or the float length of the interlacement repeat. The increase in yarn's unit length or yarn thickness can result in a higher crimp percentage. Thus, it is believed that the crimp in a diamond braid is higher than any other structures. The crimp can be affected by variables braid angle and the number of yarns as well.
2.4. Application of composites and braided composites

A composite material is an engineering material that is made up with two or more materials, which consists of a core reinforcement reinforced by a matrix [20]. The most efficient method that has been found to use fibres as engineering materials is to ‘combine a fibrous material of high tensile strength and high modulus of elasticity with a lightweight bulk material of lower strength and lower modulus of elasticity’ [21].

The fibre-reinforced composite is generally composed of three elements: the fibres, the matrix and a fine interphase region which responsible for assuring the connection between the matrix and fibre as the interface [22]. The resultant material has superior performance to that of individual materials [23].

2.4.1. Application of composites

One of the key factors that leads to increasing global temperatures is transportation which contributes to the output of greenhouse gases. Lightweight composite materials help to reduce the mass of vehicles, is one solution that can have a dramatic effect on the production of these emissions as with reducing vehicle weight, the fuel consumption reduces. The use of lightweight materials such as carbon fibre can trigger dramatic weight savings and thus reduce fuel consumption.
Composite materials have a wide range of applications in various industries. These are widely used in automobile industries (e.g. substitute of Steel & Aluminium body); Marine applications like shafts, hulls, spars (for racing boats); Aeronautical application like components of rockets, aircrafts (business and military), missiles etc.; Communication antennae, electronic circuit boards (e.g. PCB, breadboard); Safety equipment like helmets for ballistic protection.

2.4.2. **Textile composites**

Textile composites, which are also defined as textile-reinforced composite materials (TRCM), become more welcome than conventional materials because of its high weight to stiffness ratio (specific stiffness), as well as improved fatigue life, corrosion resistance, and with good design practice, reduced assembly costs due to fewer detail parts and fasteners.

Variety shapes of composite structure can be produced because of flexible fibrous structures that can be shaped easily due to their drapability. Tubular composites are
usually made of long continuous fibre rather than short fibre because the continuous fibre composites can reach the specific requirements to stiffness and weight in the products [23]. Long continuous fibres are widely used to produce composite structure by weaving, filament winding and braiding. In this project, preforms were produced by 2D (two dimensional) braiding.

2.4.3. Application of braids and braided composites

Braiding can be used for many critical applications ranging from ancient decorative belts to a variety of applications on air and spacecraft [7]. Braiding has been chosen for producing cables, ropes, laces and so on. On the other hand, braids are also used in many industrial applications such as fan blade containment in commercial aircrafts; for energy-absorbing crash structures in Formula One racing cars; as reinforcement for aircraft propellers and stator vanes in jet engines; for building lightweight frames and structures such as trusses; for use in precise manufacture of composite parts; ideal reinforcement for drive shafts and torque transfer components, such as flanged hubs; for products with changing geometries like prosthetics and hockey sticks etc. [26]. Brookstein[27] listed some of structural columns, rods, shafts, pressure vessels and plates used in traditional applications where braid enhancement has replaced conventional materials.

Braids are not limited within cylindrical structure anymore. As Branscomb et al.[28] pointed that ‘braids can be, cylindrical (round), flat, or a variety of other cross-sections’. For example, square, hollow square, I-beam, U-beam, T-beam, X-beam [29], L-beam [30] and etc. It is possible to produce more complex-shaped parts by using braiding technology [31, 32].
2.5. **Relation between mandrel position and compensation length during braiding**

During braiding process, the lengths of fibre tow from eyelet to fell point are not constant. This length variation is exactly the length that needs to be compensated by the compensator roller. The braiding machine has its own ability to compensate for length difference. So compensation length will be studied in this section.

2.5.1. **Introduction of compensation length**

As carriers move along the track, which is in a wave shape but not a circle, there is a distance variation between its nearest and furthest point to the centre of the braiding machine or from the fell point (Figure 8 left) [8]. Due to the fact that the take-up speed of mandrel is constant during braiding process, which is set manually, fibre tow will be pulled out more when a carrier moves from the nearest point to the furthest point and that will result in an extra length of fibre tow. Compensators, play its role to compensate the fibre tow during braiding and make the braiding process go smoothly.

Figure 7 (a) Complex shapes are manufactured (b) RTM (Resin Transfer Molding) technology used to manufacture complex shaped braided composite [33]
Figure 8  Schematic of front view of bobbin carrier track (left) and side view of carriers (right) [34]

Usually, mandrel is placed at the centre of the whole braiding machine. The compensation length will only be caused by variation distance from eyelets to centre of the machine. Hence the carriers are designed to compensate the amount of fibre pullback that is required due to the dancing motion of the carrier. However, in this study, the mandrel was taken off-centre of the braiding machine. This caused increase in fibre length difference in addition to the length difference caused by the carrier motion. For a successful braiding keeping the mandrel off-centre more compensation length will be needed.

2.5.2. Length from eyelet to braid ring

$l_1$ is the nearest distance from eyelet to braid ring; $l_2$ is the furthest distance from eyelet to braid ring; $l_3$ and $l_4$ is the distance from the intersection point of two bobbins to braid ring.

In order to find out the maximum compensation length between eyelets and braid ring, the difference between $l_1$ and $l_2$ could be calculated,
\[ \Delta l_c = l_2 - l_1 = \sqrt{(h_1 + h_2)^2 + d^2} - \sqrt{h_1^2 + d^2} \]  \hspace{1cm} (7) [34]

Where \( \Delta l_c \) is the difference between \( l_1 \) and \( l_2 \); \( h_1 \) is the nearest vertical distance from guide eyelet to braid ring contact point; \( h_2 \) is the distance between two guide eyelets; \( d \) is the horizontal distance from guide eyelet to braid ring contact point.

### 2.6. Braiding using non-circular braid ring

The braided composite has an advantage that their stiffness distribution can be changed by changing the braiding angle. In order to change the braiding angle on a cylindrical braided fabric, the longitudinal velocity of the mandrel and the rotation speed of the carriers in a braider should be changed. However, these changes are only in the longitudinal direction but not in the circumferential orientation. In this case, Nishimoto et al [14] presented a method (using an elliptical braiding ring instead of circular braiding ring) to change the circumferential distribution of braiding angles, which made the braiding angle in the circumferential orientation changed (Figure 9).

![Figure 9 (a) Maypole braiding machine with an elliptical braiding ring. (b) Braiding angle changes with the changes on the radius of the creating ellipses [14]](image-url)
Also, the convergence length was not constant by using elliptical braid ring (Figure 10) because if the longitudinal velocity of mandrel changes, there is some delay for actual braid angle reach the designated braid angle. Simulation the convergence length was constant; the braiding angle $\theta$ is determined only by the changes in the radius of the creating ellipse. Therefore, changing the shape of braid ring can change the braid angle distribution along the circumferential direction.

Figure 10 Schematic diagram of the convergence zone between the elliptical ring and the fell point showing change in convergence length and fell point position due to the ellipticity of the ring

Ebel and Hans [35] braided on different cross-section mandrel and found that it affect yarn path and thus braid angle. But their experimental braid angle had deviation compared to theoretical yarn path. They minimised deviations by changing shape of braiding ring. Circular and three elliptical braid ring with different aspect ratio were used to achieve it. Also, three different cross-section of mandrels (circular,
square and rectangular) were braided on. They presented that braid angle could be controlled by changing the braiding ring shape. The four different shapes of braid rings used in their study are shown in Figure 11. It could be seen that the increase in one diameter of the braid ring led to braid angle on right and left sides decrease, but braid angle on top and bottom sides increased. It was the effect of braid ring ratio on braid angle deviation. Their study showed that different cross-section mandrels all fit this result.

Moreover, ±30° and ±60° structures were braided to find that the influence of ring shape decreases with increasing braid angle. However, it was not suitable for small angle structure. Braid angle formation was irregular on ±30° braid.

In both the studies [14] [35] with elliptical braid ring, braid angle were same at opposite sides of mandrel. With the increase in major diameter of the elliptical braid ring, the angle deviation increased as well. In Ebel and Hans’ [35] study, the angle changed by using circular braid ring (Figure 11) was because of the square mandrel.
as the flat surfaces will affect the fibre deposition. [36]

2.7. Wrinkle formation on braided preform

Defects in composite materials that may be created during manufacturing tend to degrade the performance characteristics of the final product [37, 38]. There are many types of defects, such as voids, delamination, incomplete resin cure, fibre crimp, wrinkle, etc. may appear during textile composite reinforcement [39]. One of the more serious flaws that arise during forming is wrinkling [40, 41], which tend to significantly degrade the performance characteristics of the final product [42, 43]. Wrinkling would lead to a serious loss of mechanical properties [44]. Hence, reducing wrinkles in the final product in order to improve the forming of the material is one of the main aims of optimizing textile composite structures.

Figure 12 Optical microscopic image showing a circumferential cross-section of the tube. The wrinkle amplitude is twice as much as the wall. [45]
A lot of parameters can cause wrinkle, such as the number of plies, ply placement, fibre architecture, etc. during forming. Figure 12 shows a wrinkle in a braided composite tube manufactured using vacuum bagging method.

2.7.1. Causes of wrinkle formation

When the fabric is deformed in the compression direction, buckling will occur and wrinkles will be formed. Likewise, it is also a problem in fabric reinforced composite forming. Wrinkling will occur when the preform is required to shear too high to form a particular geometry [37, 46]. The locking angle can be used to describe the potential of a fabric to produce a particular surface. Prodromou and Chen [37] defined the locking angle as ‘the angle achieved just before the onset of buckling’. The formation process of wrinkle is illustrated in Figure 13. They observed that the deformation behaviour of fabric can be divided into two parts: when a low load is applied, trellising will occur before fabrics lock-up; while applying a sudden increase in load, out-of-plane bending (wrinkling) occurs after lock-up. Some other in-plane shear studied also analysed wrinkling focusing on locking angle as well [47, 48].

![Figure 13 Wrinkling due to shearing. Wrinkle appears after the locking angle achieved [49]](image-url)
Lebrun et al. [50] used a bias-extension test to measure the shear properties. During testing, the specimen was applied a pure intra-ply shear deformation, where the angle between tows decreased gradually until it reaches locking angle and formed a wrinkle. Zhu et al. [40] proved Prodromou and Chen’s opinion. They figured out that two deformation types, in-plane shear and out-of-plane wrinkling, may take place during the textile fabric formation. They built up a theoretical model based on previous specimen to see how the fibre sheared under stretching. Boisse et al. [49] applied load on a unit woven cell and analysed the role of the three rigidities of woven fabric in wrinkling simulations. The three rigidities are tensile, in-plane shear and bending. They found that tensile rigidity was usually avoided in forming process. The in-plane shear stiffness increased when the shear angle became larger. Bending stiffness played a significant role in wrinkle size.

2.7.2. Wrinkle caused by bending

Different cross-section of mandrels can affect the braiding angle contribution along circumferential direction. Also different shape of the mandrel (curving mandrel) can influence the braiding angle. However, when braiding on these curving mandrel, Hubert, Poursartip[51] found that angles processed on convex tools in general exhibited thinning at the corner, whereas thickening at the corner was observed for angles processed on concave tooling. Fibre movement during the curve process which causing the changes in geometry and properties, and leading to stresses and distortion. As shown in Figure 14 (a) (b), the presence of wrinkle resulted in the higher thickness at the corner. The resin that is shown in Figure 14 (c) was created because of the bag bridging at the corner. Resin filled the gap that created by bag bridges. Figure 14 (d) shown bag indentation at the corner of concave tool.
Figure 14 Microphotographs of the cross section of samples with defect at the corner of the laminates (a) (b) wrinkles appeared on different materials (convex tool). (c) (d) wrinkles appeared on different materials (concave tool)

Figure 15 Photographs of cross section of samples showing external wrinkle
The materials layers between preform surface and the bag can form wrinkles due to the curvature of the mould surface. Typically it was more difficult to eliminate the wrinkle with a concave tool.

Generally it is assumed that the fibres on longitudinal direction are under an amount proportional tension to their distance from the neutral axis, which is also, happens to the centroidal axis. However, in the experiment, it was found that the neutral axis moved a little bit forward to tension side.

![Neutral axis](image)

Figure 16 Mechanics of the bending: analogy with a solid rod. The neutral axis moves toward outer surface of bend [52]

According to Sharma et al. work, it was no longer linearly proportional because of the limit to the fabric extension [52]. It would cause the neutral axis not coincide to the centroidal axis (Figure 16). If the maximum tension was same as the maximum compression, the neutral axis would be same as centroidal axis. But for most fabric,
the extension was limited. The neutral axis was usually above the centroidal axis. They also indicated that the extension on outer surface of a circular bent tube applied along both the length direction and the cross-section direction of the preform. Here ‘Brazier effects’ were come up with which cause a circular cross section deformed to be an oval shape.

Karman [53] indicated that when the tube is subjected to bending, for example, in order to increase the curvature, the stress will have a tendency to push the components on both sides of the transverse section towards the neutral surface. Thus, the farthest material from the neutral axis is enabled to shirk its effect and greatly reduce the stress, and the maximum stress will occur at point closer to the neutral axis.

2.7.3. Minimising wrinkles

It was assumed that fabrics having higher friction coefficients will have larger locking angles, while those having lower friction will have smaller locking angles [37]. According to Boisse et al.’s study, it shows that the bending stiffness only determines the shape of wrinkles. Hence the increase of bending stiffness can lead to an increase of wrinkle size.

According to Yu et al [54], the blank holder force can be used to prevent wrinkling as an independent optimization parameter. Lin et al [55] found two ways to prevent wrinkling during composite forming. One is optimizing processing parameters and the other one is by material selection. They focused on the effect of various blank holding forces on wrinkling and they demonstrated that using the blank holder profile can be used to minimize wrinkling because of the orthotropic anisotropic behaviour of textile composites. In another study [56], a tubular woven fabric
preform was draped over a bent shape (Figure 17). In the study it was observed that the fabric at compression side produce ‘wrinkles’. The authors proposed an algorithm to re-engineer the fabric by changing weft density. In this study, changing braid angle around the circumference will provide similar opportunity to decide bending side to prevent wrinkle formation.

![Figure 17 Weave Modifications to Remove Wrinkles](a) Normal fit. (b) Re-engineered fabric [56]

2.8. Conclusions

The braid parameters described in this chapter, play a sufficient role in determining braid geometry and structure. These factors influence each other and collectively affect the braid density. From the studies conducted in literature, it has been found that the braid angle distributions along circumferential direction can be changed by using an elliptical braid ring instead of a circular braid ring. If an elliptical ring rather than the circular ring is used, the braid angle in the axial direction remains constant, but in the circumferential direction, the braid angle will change.
With the wide use of carbon fibre reinforced composites in the industries, there are also demand for non-linear and complex shape products. During complex shape manufacturing, the literature shows that unbalanced force leads to fibre shearing and result in wrinkle formation. Although literature reviews were carried out on wrinkle for textile preforms in composites, no studies on wrinkle for braided composite manufacturing were found. In this study, based on the findings of the literature, methods to rearrange the braid parameters will be investigated to minimise wrinkle formation in final products.
3. Experimental Methodology

3.1. Introduction

A brief introduction to experimental process steps of this project has been presented at the early part of this chapter. The preparation including bobbin winding, braiding and vacuum bagging.

The carbon fibre used in this project was T700SC 12000 60E, and the properties of this fibre is shown in Table 1.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength</td>
<td>4900 MPa</td>
</tr>
<tr>
<td>Elastic Modulus</td>
<td>230 GPa</td>
</tr>
<tr>
<td>Strain</td>
<td>2.1 %</td>
</tr>
<tr>
<td>Density</td>
<td>1.80 g/cm³</td>
</tr>
<tr>
<td>Filament Diameter</td>
<td>7 µm</td>
</tr>
<tr>
<td>Number of filaments in a tow</td>
<td>12000</td>
</tr>
<tr>
<td>Fibre tow Count</td>
<td>800 tex</td>
</tr>
</tbody>
</table>
3.2. **Braiding preparation**

3.2.1. **Mandrel selection and preparation**

In this project, metal mandrel was not chosen because the over-braided mandrel should be able to be bent flexibly by using bending machine, which will be mentioned in Chapter 5.

![Figure 18 Wrinkle appears on the metal after bending](image)

However, wrinkle formation after bending is a serious issue which cannot be ignored. As shown in Figure 18, the wrinkle that appears on the mandrel will definitely influence the braids structures as well as the properties of braids. Hence, flexible tube was used as mandrel rather than metal. Considering that mandrel will be placed in the oven with braids for composite manufacturing, the operating temperature, glass transition temperature ($T_g$) as well as melt temperature should be suitable for composite manufacturing procedure. The glass transition temperature ($T_g$) of Polyvinylchloride (PVC) are about 82°C and the resin curing temperature was 80°C.
Since PVC is an amorphous thermoplastic, it softens gradually as temperature rises. The melt point of PVC is between 100-260°C. PVC tube is flexible enough to be bent to a certain curvature without cross section shape change. Due to these factors, PVC tube was selected as suitable mandrel material for this project. Also wrinkle will not be created after bending. In this study, 25.4 mm outer diameter PVC tube and 12.7 mm outer diameter PVC tube were selected as mandrels.

In general, the mandrel used for braiding is required to be straight. The PVC tube was received in the roll form and hence it needed straigtening. In this study, an aluminium tube was inserted into the PVC tube to hold it and keep it straight during braiding process. Before that, the PVC tube was put in oven and temperature was raised to 82°C. Once the tube reached the $T_g$, it was cooled down to room temperature. The process made the PVC tube mandrel straight.

Figure 19 PVC tube used in this study
3.2.2. Bobbin winding

In this project, for producing a regular braid structure (2/2) 48 bobbins were wrapped with carbon fibre. The machine used for winding is Herzog rewinding unit USP 300 Eltra as shown in Figure 20.

3.2.3. Braiding

Each bobbin is mounted on a carrier and the fibre tow was passed around the compensator roller and other guides. During braiding as the carrier moves in a serpentine path, the fibre length between the carrier and braid fell point varies. As a result the fibres lose tension and become slack. To prevent this, the carrier has spring compensation method. The compensation length of the carriers used on the machine is 210 mm. This means a length of up to 210 mm slack can be pulled back by the compensation roller to under tension. The braiding machine has 48 carriers and the
machine was full of bobbins to produce a 2/2 (regular braid) structure. The roller tensions were set by adjusting the torsion spring to a force of 1.5N. The tows were passed through the braid ring and all were placed onto a mandrel. The ends of the tows were secured onto the mandrel and braiding was carried out manually to set a starting point.

Figure 21 The Cobra braiding machine during manufacture of a specimen

The mandrel was clamped at one end by thread clamping system as tightly as possible to prevent the slippage of the mandrel during braiding. The mandrel slippage during braiding can lead to angle deviation from the setup. Braiding take-up was controlled by an integrated computer operating CAM software developed by Trio motion Ltd.

This automatic motion was determined by the input parameter, including take-up speed and carriers rotation speed. The carriers were driven at a constant rate of 0.63
rad/s. The take-up speed of mandrel was driven at a specific speed, which is depending on the desired braid angle. It was calculated by using equation 1.

The machine was kept at these speeds until the fell point approached the free end of the mandrel, at which point the machine was stopped manually. As the braiding was completed, the braid was tightly wrapped with a transparent adhesive tape to avoid slippage of the braids, which is a key step in preventing the disruption of the braid angle.

At this point the mandrel could be removed for a single layer braid. However, two layers were needed to compare with single layer. The process was same as multiple layers. Outer diameter was measured by using digital calliper. The second layer was then braided in the same manner with the take-up speed adjusted to produce a constant braid angle.

In this study, one 25.4 mm diameter tubes and one 12.7 mm diameter tubes were braided to produce ±45° structures. Another two different sizes of tubes had two layers of braids to identify the difference between one layer braid and two layer braids.

3.3. Composite fabrication

3.3.1. Introduction

All preforms were consolidated by using vacuum bagging method. Composites manufacturing can be summarised as two stages: preform manufacturing and resin infusion. The preform is manufactured in braiding process in this study as explained in previous section. The steps of vacuum assisted liquid resin infusion and curing is described in the following sections.
3.3.2. Resin formulation and degassing

High curing temperature epoxies are widely used in aerospace composite manufacturing. The epoxy resin was formulated by mixing the resin (Araldite LY 564) and hardener (Aradur 2954) at ratio 100:35 by weight in a container.

After mixing of two parts, the container was put in a vacuum chamber. As the vacuum pump draws the air out of the chamber, the degassing process removes all the air bubbles added during mixing.

3.3.3. Resin infusion

The overbraided mandrel was covered using release fabric, also known as ‘peel ply’, is the first layer. It is used for easy separation of the composite from other infusion aid materials after resin infusion. The infusion mesh which is usually highly permeable warp knitted fabrics overwrapped on top of the release film wrapped braid. It acts as a medium to transport the resin from inlet to outlet, also exhausts the volatiles, air and moisture. The outermost layer is a nylon bag film that acts as vacuum membrane. The bagging film is sealed using sealant tape on top of the mandrel keeping the preform and other infusion aids inside. This acts as an envelope. Inlet and outlet tube is connected to this envelope to draw resin into the braided preform and remove air, moisture, solvents and volatiles respectively.

Two resin traps were made by sleeve bagging film enclosed an absorbent non-woven fabric. One was connected to the outlet infusion tube to absorb excess resin. The other one had a valve pierced through the bag to connect with vacuum pump.
Followed by closing all the open tubes for air to the bag film, the valve was connected to the vacuum pump. The vacuum environment was achieved after dropping the air out. The process was completed by delivering the resin to the preform from inlet tube and closing the vacuum trap and inlet tube once the preform was full permeated in the resin.

Upon completed infusion, the whole system was then put into the oven for curing cycle duration. Once fully cured all bagging materials were discarded.

3.3.4. Curing and demoulding

Once the resin infusion was completed, the resin infused mandrel was kept in an oven. The curing and post-curing was carried out at 80°C and 140°C respectively. After curing cycle had completed, the oven was switched off and temperature was decreased
slowly to bring back to the room temperature. Once the part was taken out of the oven, all the materials added on the preform was removed to separate the composite.

Figure 23 Cure cycle of epoxy resin (Araldite LY 564 and Aradur 2954) for composite manufacturing. The dotted line represents the uncontrolled cooling within the oven chamber

After all materials and PVC mandrel was removed, the composite tube was cut along its length. In this study, composite tube braided by using circular braid ring and that braided by using elliptical braid ring were compared.
3.4. Conclusions

Fibre tows were interlaced on mandrel, the shape of the braid was determined on the shape of mandrel. Flexible hollow tubes were used in this study as this kind of tubes were easily to be bent in the next experiment. The winding machine could be used to transfer the fibre from fibre package to 48 bobbins. Braiding process was controlled by an automatic motion, which was determined by input take-up speed and carriers rotation speed. Then the desired braid angle could be produced. Afterwards, bending process that will be discussed in Chapter 5 was followed. After preforms were produced, all of them were consolidated by using vacuum bagging. Preforms were sealed in a vacuum bag with release fabric and mesh covered. Resin infusion happened after resin degassing. This process removed all air bubbles. After curing and demoulding, composite manufacturing process was completed. In the end, the tubular composites were cut along its length to see whether wrinkle appeared or not.
4. Effect of Linear Compression on Braided Preforms

4.1. Introduction

In this study, the over-braided mandrels were subjected to bending which resulted in a tension and compression on the inner and outer bent of the braided sleeve. The biaxial braid architecture has a phenomenon of fibre shearing while suffering tension or compression force. When the braid is axially stretched, the mechanism of deformation is mainly sheared and parallel to each tow [58]. The “Chinese finger trap” principle was demonstrated in a recent study [59]. When a tension force applied on the braid, the length increase can result in decreasing of fibre orientation and subsequently braid diameter increases, vice versa. A ‘scissor effect’ [58] was presented, which is that as the braids are stretched, the tows scissor like the shape of a trellis. In this chapter the braid tow scissoring in relation to tension and compression is presented.

4.2. Prediction of biaxial braid angle under compression/tension loading

Owing to the fact that compressions at the inner bend causes braid angle increases while compressing, this also leads to diameter change. In order to find out how the braid angle and diameter change with compression, relationship among braid angle, diameter and length could be developed.
Figure 24 (a) Regular braid structure (b) Considering the braid unit cell acts as a trellis in which the intersecting four sides are pivoted [60] (c) unit cell schematic (d) unit cell schematic under compression assuming the sides are pivoted [61]

In this study, a unit cell was regarded as a trellis with a diamond shape.

\[
\alpha = \tan^{-1} \frac{pr}{qs} = \tan^{-1} \frac{C}{L} \quad \text{(8)}
\]

Where: \( L \) = Length of a unit cell; \( C \) = Width of a unit cell; \( \alpha \) = Braid angle
In case of a uniform cylindrical braid structure, when \( \alpha = 45^\circ \), the unit cell widths on all four sides are equal. With equal sides, the diagonals are equal too. Therefore,

\[ pq = qr = rs = sp = a \]  \hspace{1cm} (9)

and

\[ pr = qs \]

So,

\[ L = C \]  \hspace{1cm} (10)

Hence,

\[ L^2 + C^2 = 2a^2 \]  \hspace{1cm} (11)

When the unit cell suffers a compression force, the diagonal distances \( pr \) and \( qs \) changes. For the fibre structure, fibre slippage will happen at the cross over points hence the position of the intersection will not remain fixed. The slippage can result in change in fibre structure parameters such as fibre tow width, spacing, etc., which can influence the unit cell dimension. In addition, due to the interlacement of braid tow, there will be frictional resistance to fibre shearing as well. In this study it is assumed that the four sides of the unit cell remain equal during compression or tension. Also, the four points at the boundary of the unit cell acts as pivots to form a trellis changing the position under compression or tension without any resistance or slippage.

Considering the above assumption of pivoted sides, the diagonal distances will change under compression (Figure 24d), so,

\[ L_1^2 + C_1^2 = 2a^2 \]  \hspace{1cm} (12)

So, from equation 13 and 14,

\[ L^2 + C^2 = L_1^2 + C_1^2 \]  \hspace{1cm} (13)

If the compressive strain is \( \varepsilon \), the unit cell length after compression \( L_1 \) can be written as,
\[ L_1 = L (1 + \varepsilon) \quad (14) \]

In case of a regular braid with \( N_c \) number of carriers, the number of unit cells in the circumference,

\[ n = \frac{N_c}{8} \quad (15) \]

So the width of a unit cell,

\[ C = \frac{\pi D}{n} \quad (16) \]

In the above equation, \( D \) is the braid diameter.

Similarly, the width of the compressed unit cell,

\[ C_1 = \frac{\pi D_1}{n} \quad (17) \]

The compressed braid diameter can be calculated from equation 12 as follows,

\[ C_1 = \sqrt{\left( (L^2 + C^2) - L_1^2 \right)} \quad (18) \]

Substituting the \( L_1 \), \( C \) and \( C_1 \) from equation 16, 17 and 18 into equation 15,

\[ D_1 = \sqrt{\frac{n^2 L^2}{\pi^2} (1 - (1 + \varepsilon)^2) + D^2} \quad (19) \]

Under compression, alongside the change in diameter, the braid angle will also change. As the angle changes to \( \alpha_1 \) when the length and width changes to \( L_1 \) and \( C_1 \) respectively, from equation 10,

\[ \alpha_1 = \tan^{-1} \left( \frac{C_1}{L_1} \right) \quad (20) \]

Substituting the \( L_1 \) and \( C_1 \) from equation 16 and 18 into equation 22,
\[ \alpha_1 = \tan^{-1} \left( \frac{\pi D_1}{nL (1 + \varepsilon)} \right) \]  

In the above equations, D is the initial braid diameter and \( D_1 \) is the braid diameter under loading, \( L \) is the initial length of the unit cell (Figure 24c) and \( \varepsilon \) is the longitudinal strain under loading. The notations, \( \alpha, \alpha_1 \) and \( n \) indicate initial braid angle, braid angle after deformation and the number of unit cells around the circumference respectively.

4.3. Linear tension and compression loaded on sleeves

![Device used for linear compressing of braid](image)

Figure 25 Device used for linear compressing of braid. Blue arrows are compression forces
In order to find out how the braid parameters change under linear compression, a braided sleeve was compressed on a mandrel to simulate the situation that happened on compression curvature during bending.

The device shown in Figure 25 was used in this experiment. The whole device consists of three parts: supporting base, shaft and a ring that slides onto the shaft in order to provide necessary displacement. The support works to stop sleeve to move. The shaft plays a role as a mandrel. Pressing the ring by hand, a linear compressive force could be applied on the sleeve. During compression loading, braid angle and diameter were recorded after every 10 mm change.

Figure 26 Images show the linear compression of a braid. The two ends of sleeve were folded instead of securing with cello tape which could apply a boundary condition and prevent free movement of fibre during compression.
A 200 mm long braided sleeve was placed on the 25.4 mm diameter shaft and connecting with supporting base and compressing ring Figure 26. Two ends of the sleeve were folded to prevent fibre tows from getting released. The initial braid angle was ±45° and outer diameter was 26.67 mm. The sleeve was pressed gradually, a compressing force was applied on sleeve along its axial direction, which caused sleeve shorter and increased the braid angle as well as outer diameter. When the sleeve was compressed to 190 mm, the braid angle and outer diameter could be recorded. Continue to compress the sleeve to 180 mm, 170 mm, 160 mm and so on until the braid angle did not increase. The corresponding braid angles and outer diameters were recorded after each step.

As for linear tension, there is no shaft used for holding. The sleeve was a hollow structure and the tension force was applied manually. A sleeve of 200 mm length was placed on the table and taped two ends of the sleeves. Holding two ends of the sleeve and applying a tension force manually along its axial direction. The braid angle and diameter data were recorded every 10 mm change in length as well. Recording the braid angle and outer diameter value after the length of sleeve was increased to 210 mm. Continue to stretch until the product was stretched to 220 mm, 230 mm and 240 mm, respectively, to record the corresponding braid angle and outer diameter.

The diameter of 12.7 mm sleeve was measured by using the same way as 25.7 mm diameter sleeve. The sleeve was compressed and stretched respectively. The braid angle and outer diameter were recorded after each step.
Figure 27 Linear compression force applied on a braided sleeve. Initially braid angle is ±45°. The decrease in length leads to increase in braid angle and braid diameter after compression.

Figure 28 Linear tension force applied on a braided sleeve. Initially braid angle is ±45°. The increase in length leads to braid angle and braid diameter decrease after compression.

As shown in Figure 27(a) and Figure 28(a), braid angle was ±45° without any loading. After compression, the decrease in braid length resulted in increasing of braid angle and subsequently led to braid diameter increase [Figure 27 (b) (c)]. On the contrary, when a tension force loaded on a braided sleeve [Figure 28(b) (c)], braid length increase led to braid angle as well as braid diameter decreased.
4.4. Measurement

4.4.1. Braid angle measurement

Braid angle was measured by using a digital protractor. This Wixey Digital Protractor shown in Figure 29(a) is precise and convenient for measuring braid angle. It measures angles with ±0.1° resolution accuracy. As shown in the Figure 29(a), the edges of the digital protractor were aligned to the two adjacent tows helically running along clock and anti-clockwise.

Figure 29 (a) Braid angle measurement using digital protractor (b) Braid diameter measurement using digital calliper

According to the definition of braid angle, the braid angle is half of the angle shown on screen. In order to improve accuracy in the measurement ten data values were collected along its length for the same angle measurement.
According to the equation 21, braid angle under compression and tension can be predicted as shown in Figure 30. When a uniaxial compression and tension force applied on the sleeve, braid angle could be calculated from the relationship between angle and axial displacement.

Figure 30 Relation between displacement and angle. Braid angle is ±45° when displacement is 0. Braid angle increases under compression and decreased under tension until it reaches to locking angle. The dotted red line when axial displacement is beyond 40 mm means the sleeve cannot be stretched any more

In order to prove this equation, a braid sleeve with 200 mm in length, ±45° of braid angle was prepared. At this stage, no force is applied on the braids. Then braid angle
increased under linear compression and decrease under linear tension. As shown in Figure 30, axial displacement is 0 while no loading applied on the sleeve. Under compression, change in length led to displacement change, which result in braid angle increase, vice versa. However, braid angle rose while the braids reaching to jammed state. At this stage, braid angle reaching to locking angle. Then further loading would result in wrinkle formation and the braid angle maintained steady.

4.4.2. Braid diameter measurement

Braid diameter was measured by using digital calliper (Figure 29b). The digital calliper gives a direct reading of the distance measured with ±0.01mm accuracy. When measuring the braid diameter, one important thing should be focused on is measuring without any pressure. Care was taken during the diameter measurement to prevent applying extra compression by the callipers jaw on the surface of braids. Also, the braids consist of a lot of interlaced filament fibre tow, which results in an uneven surface as shown in Figure 31. But the width of the calliper jaw is much smaller than the width of fibre tow. It made that the jaws of the calliper were easily touch the gap that between two tows interlaced. In this case, the measured diameter would be smaller than the real value. It was ensured that the calliper jaws did not touch on the gap position between fibre tows. The braid diameter measurement was carried out at the same points as braid angle measurement.
Diameter could be predicted as well. By using equation 19 that came out in Section 4.2, the relation between diameter and axial displacement is shown in Figure 32. Diameters change under compression and tension were also recorded to prove diameter equation. Braid diameter increase with the increase of the braid angle. As soon as the braid angle reaching to the locking angle, braid diameter would not increase anymore.

The original length was 200 mm, at which time the sleeve was not deformed. When the compression force applied on the sleeve, the axial displacement increased nonlinearly. The greater the deformation of the braids, the smaller increase rate of displacement. Compare the Figure 30 and Figure 32, when the displacement increase to about 80 mm, the angle increased to locking angle and stopped increasing further. As for diameter, it stopped increasing at the point that displacement increase to about 80 mm as well. Hence, diameter increased with the increase of braid angle under compression.

As for tension, diameter decreased with the increase of displacement. According to the prediction, in the case of stretching, the decrease rate of diameter went faster. However, it was found in the experiment that when the strain increased to 40, the
diameter was not reduced because the density of the fibre tow got to maximum. Also, the increase in braid angle led to cover factor (CF) increase. The maximum CF is 1. Once the CF increased to the maximum, it could lead to braid being unable to be stretched.

Figure 32 Relation between displacement and diameter. Braid diameter increases or decreases under compression or tension respectively until braid angle reaches to locking angle.

Comparing the change of braid angle and diameter with compressing length, it was obvious that the simulation curve fits the experimental results very well. So
equations are effective to be used to predict the braid angle and diameter under compression or tension.

4.4.3. Areal density and yarn spacing

A 200 mm long braid sleeve weights about 11.1 g. The initial areal density was about 663 g/m². The mass of braid did not change under tension or compression. So the change in surface area changed the areal density.

![Figure 33: Areal density increased with the increase of displacement.](image)

When the braid angle was ±45°, the braids had the lowest areal density. With the tension or compression force applied on the sleeve, the increase or decrease of the braid length led to decrease in surface area. Also the tow width changed to smaller value as the angle increased or decreased. As a result fibre packing increased in a given surface area. So the areal density increased. However, when the braid angle reached to locking angle (displacement is -80 mm), further loading could result in
wrinkle formation. In that case, the surface area could not be measured or calculated. Thus areal density could not be calculated.

![Figure 34 Way of yarn spacing measurement](image)

Yarn spacing is an important quality characteristic in textiles. It refers to the distance between two adjacent fibre tows in braids. In this study, yarn spacing was measured followed the way shown in Figure 34. As 2/2 structures were produced in this study, the initial cover factor was nearly 1, which means the mandrel was full covered. When tension or compression load applied on a braided sleeve, cover factor could not increase anymore. In this case, yarn spacing is nearly the same as tow width. As tow width decreased under compression, yarn spacing also decreased. However, as soon as the braid angle reached to locking angle, further loading could not lead to change in tow width. Thus, yarn spacing did not change as well. On the contrary, the number of fibre tows remained same. The tow width decreased under tension because braid diameter reduced. So yarn spacing decreased as well.
4.5. Conclusions

In this study it is assumed that the unit cell keeps its four sides equal and rotates at four points through acting as a trellis without major resistance or slippage during compression or tension until it reaches the lock limit. Then braid angle and braid diameter under loading can be calculated. In this case, the linear compression process as well as linear tension process can be used to simulate the braid parameter (especially braid angle and braid diameter) change happened at compression side and tension side while bending because braids suffered compression and tension as well during bending. The braid angle could increase when a compression force loading on a braided preform. When it increased to a certain extent (braid angle reached to locking angle),
locking angle), it stopped increasing. Meanwhile, braid diameter did not increase any more until the braid angle reached to locking angle. Then further compression could result in wrinkle created on braids. On the contrary, during tension loading process, braid angle and diameter decreased but that reduced until the sleeve could not be stretched more. The change in braid angle and diameter during compression were higher than that during tension because when compression load applied on the preform, more space were created between interlaced fibre tow and the mandrel, but during tension process, more friction were created between interlaced fibre tow and the mandrel. The frictional resistance resulted in smaller changes of braid angle when compared to compression side. Similarly during bending, compression and tension force applied at inner and outer sides of the curvature. The change of braid angle observed during linear compression and tension will be compared with the changes after bending as studied in Chapter 5.
5. Effect of Bending on Braid Parameters

5.1. Introduction

In this chapter, braided tube were bent to 90° and 180° to studied the effect of bending on braid angle and braid diameter formation. Braid angle and diameter data were collected from tension side, compression side and neutral axis. Two sizes of tubes (25.4 mm diameter and 12.7 mm diameter) were bent to illustrate the braid angle and diameter formation on different size of preforms. Meanwhile, 1 layer braids and 2 layers braids were bent to find out the effect on braid parameter formation.

5.2. Relationship among braid angle, diameter and length of braids

During bending, as the inside radius \( R_i \), which is also known as bending diameter radius, (Figure 36) is smaller than that of the outer \( R_o \) and neutral axis radius \( R \), the reduction in length at inner bend leads to compression (Figure 36). The outer bend is similarly subjected to tension due to the increase in length from the centre line.

If the degree of bend is \( \theta \), braid radius is \( r_b \), total braid thickness is \( t_b \), \( R_i \) is the inner diameter of the braid (or mandrel dia) and the bending die radius is \( R_d \), the length of the braided tube at the inner curve \( (L_i) \), neural axis \( (L) \) and outer curve \( (L_o) \) can be calculated as follows.
As $R_i < R$ the reduction in length ($L_i < L < L_o$) at inner bend leads to compression on the braid. The outer bend is similarly subjected to tension due to the increase in length ($L_o > L$) from the centre line.

![Diagram of a 90° bent tube][1]

In order to study the effect of bending, initially braiding was carried out using a circular braid ring and keeping the core at the centre of the ring. This is a standard practice for preforming using braiding process. The braiding process was executed following Section 3.2.3. For the ease of bending, PVC tube was used for the over-braiding purpose. After single layer braiding, the over-braided PVC tubes were bent.

\[
L_i = (R_d + t_b) \theta \\
L = R \theta = (R_d + r_b) \theta = (R_d + R_i + t_b) \theta\\
L_o = R_o \theta = (R_d + 2r_b) \theta = (R_d + 2(R_i + t_b)) \theta
\]

Figure 36 Schematic of a 90° bent tube [61]
to 90° and 180° respectively. Then braid angle and diameter measurement were done around the bending radius of tube.

5.3. **Bending machine**

A hydraulic pipe bender was used to ensure consistent bending process between samples. The machine used for bending is Clark hydraulic 12 Ton pipe bender as shown in Figure 37. This bender consists of a frame, 12-ton bottle jack, hex bolt, guide roller, hitch pin, bending dies and jack handle. It is a powerfully built, easy to use machine for bending all manner of steel pipe and tubing up to 180°. This bender can be used on a variety of pipework installations and for general engineering applications. A hydraulic pump is fitted within the heavy duty steel frame. Pipes could be bent into different angle by changing different bending dies. In this project, only 90° and 180° bending were studied.

![Figure 37](a) Top view of a carbon fibre braided core on bending equipment (b) Hydraulic bending equipment used for this study
5.4. **Bending process**

A 25.4 mm outer diameter tubes and 12.7 mm outer diameter tubes were chosen for braiding and corresponding dies were used on the bending machine. Before bending, the original tube was in circular cross-section shape. But after bending, the cross-section shape deformed from circular shape to an oval shape.

During braiding process, an aluminium tube was inserted into the hollow tube to ensure the cross section of outer PVC tube was circular. The aluminium tube was taken off before bending. In order to prevent the circular tube cross-section flattening to an oval shape during bending, the over-braided PVC tubes were filled with sand.

Figure 38 Cross-section of braided tube changed after bending. ‘Brazier effects’ could not be eliminated by filling the tube with sand but it was improved. Also it was verified that wet sand had better effect than dry sand.

Once finishing the braiding process, the braided tube was removed from braiding machine and filled with wet sand. Two ends of the tube were sealed with rubber bungs to keep the sand inside and stainless steel hose clamp was used to keep the bungs in place. The clamps were also used to tie a string to keep the tube in bent
shape for measurement. Before bending, braid angle and diameter was measured and recorded in order to compare with the data after bending. The first step of bending process is opening the hydraulic value by turning it anticlockwise to secure the guide rollers in place with the ram in its lowest position. When the tube was ready to be bent, placed the tube on the die. Then the hydraulic value was closed by turning it clockwise fully and pumps the operating lever gently by using hitch pin. After bending the tube to 90°, the two ends of the tube were connected with a string, which will keep the tube with this shape. The hydraulic value could be opened when completed, thus allowing the product to be removed. The braid angle and outer diameter of the curve section were measured. The measurement methods were discussed in Section 4.5.

After the measurements were taken from a 90° bent tube, the tube was placed back on the die the bending operation was repeated to bend the tube to 180°. The string length was adjusted to ensure that the tube could be kept in this shape after removing it from the dia. Then measuring the parameters and recording the values.

Figure 39 Bent tube. Tubes were bent to 90° and 180° respectively
5.5. **Measurement**

All samples were measured in ten points with even distance along the longitudinal of mandrel. As shown in Figure 40, the inner side is compression side; the outer side is tension side. The braid angle measurement was carried out at both tension and compression side and along the neutral axis on both sides. The diameter was measured on two opposite sides. All data were all presented in Section 4.5.

![Figure 40 Schematic of a 180° bent tube indicating different bending parameters](image)

The braid angle and diameter were all measured before bending. However, on curvature section, these values were changed after bending. So data was collected on the same point at curvature section to find out the braid angle and diameter change after bending.

5.6. **Braid parameter formation**

Generally, using a circular braid ring braiding on a cylindrical mandrel, the braid angles will keep constant on both along the length and circumference direction. However, when the tube is bent to 90° or 180°, forces were applied to different side
of the tube. During bending, one side of the tube goes in compression, which were called ‘compression side’, the opposite side in tension was called ‘tension side’ and other two sides were applied neither compression nor tension, so they were called neutral axis.

Figure 41 Compression side, tension side and neutral sides at the curvature section after bending

Because the tube was straight before bending, the lengths of tube along any axis were same. After bending, the length of braids along neutral axis did not change. As for compression side, the braid was compressed and become shorter, the braid angle would increase as observed during the linear compression of braid in the previous chapter. But for tension side, the braid was stretched and that force made the length of braid become longer. This resulted in smaller braid angle similar to the observation of linear tension of braided sleeve.

The bent tube was presented in a curve shape, which indicated that the force applied on the tube was not evenly distributed along its length. Thus stress irregularity would eventually cause the braid angle changed gradually from two edges to the centre of the curve. So the braid angle at the centre of the whole braids has the largest
deviation. On the other hand, the length of braids along neutral axis did not change, so that the braid angle and braid thickness did not change as well.

In general, the braid thickness is constant at any position of the braids. However, it will only be achieved under standard conditions. Once the tube was bent, horizontal force was applied to the tube at tension and compression side, which would cause the braid thickness to be changed. Different braid angle as well as tension that applied on the fibre tows would result in different thickness. Thus, at compression side, decreased length of braids caused higher braid angle and increased thickness. But at tension side, increased length of braids resulted in lower braid angle but reduced thickness.

5.7. **Effect of bending on braided parameters**

In order to find out how the braid parameters change before bending and after bending, braid angle and outer diameter were measured. These parameters were measured for all the braids produced in the whole experiment at compression side, tension side and along the two neutral axes before bending and after bending. Due to the fact that the braid angle produced by braiding machine was controlled by machine setting, all these samples had same braid angle ($\pm 45^\circ$) before bending.

Figure 42 shows that along the bending curve a gradual change in braid angle was observed from the edge of the tangent to the centre of the bending curve. On the compression side, the maximum angle was observed at the centre of the bending arc and the decrease in angle on the tension side was observed with the lowest angle located at the centre of the bending curve. At compression side, the braid angle
increased to as high as ±54°. This angle is below the locking angle observed during linear compression at which the wrinkle appeared.

![Diagram showing braid angle formation after bending](image)

Figure 42 Braid angle formation after bending

Two mandrels of 25.4 mm diameter and two mandrels of 12.7 mm diameter were chosen to be braided. The mandrel details are shown in Table 2.
Table 2 Outlines the details of tube braiding

<table>
<thead>
<tr>
<th>Tube number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mandrel Diameter</td>
<td>25.4 mm</td>
<td>25.4 mm</td>
<td>12.7 mm</td>
<td>12.7 mm</td>
</tr>
<tr>
<td>Number of layers</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

As shown in Table 2, #1 and #3 tubes had single layer, #2 and #4 tubes has double layers. When compared braid angle formation on #1 and #2 tubes or compared the braid angle formation on #3 and #4 tubes, the effect of multiple layers on braided parameters could be found out.

Figure 43 Schematic shows braid length change under compression of a multilayer braid

As shown in Figure 44 and Figure 45, the change of braid angle on different diameter tubes followed the same trend for single layer. In both cases, two layers were braided to observe the effect of bending on a case of multilayer preform. The change in braid angle was significantly higher for a two-layer braid than a single layer braid. In a two layer braid, in compression side, the outer (i.e., second) layer
The bending radius is lower than the first layer. As a result, the braid length under compression \( (L_i) \) is also lower than that of the first layer braid. This can be calculated by using equation 22.

For a 2 layer braid, the length of 2\(^{nd}\) layer braid under compression will be as follows where \( t_n \) indicates the thickness of the \( n^{th} \) layer.

\[
L_i = (R_d + t_n) \theta = (R_d + t_2) \theta
\]  \hspace{1cm} (25)

Similarly, for the 2 layer braid, the length of 1\(^{st}\) layer braid under compression will be as follows where \( t_b \) indicates the total braid thickness as shown in the Figure 43.

\[
L_i = (R_d + t_b) \theta = (R_d + t_{1+2}) \theta
\]  \hspace{1cm} (26)

Table 3 Length change under compression on a multilayer braid

<table>
<thead>
<tr>
<th>Layer</th>
<th>Bending die radius ( (R_d) ) (mm)</th>
<th>Braid radius ( (t_b) ) (mm)</th>
<th>Degree of bending ( (\theta) )</th>
<th>Braid at neutral axis ( (L) ) (mm)</th>
<th>Braid length under compression ( (L_i) ) (mm)</th>
<th>Compressed length from neutral axis (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60</td>
<td>13.34</td>
<td>180° (( \pi ))</td>
<td>232.7</td>
<td>192.9</td>
<td>39.8</td>
</tr>
<tr>
<td>2</td>
<td>60</td>
<td>14.12</td>
<td>180° (( \pi ))</td>
<td>232.7</td>
<td>190.8</td>
<td>41.9</td>
</tr>
</tbody>
</table>

The linear compression experiment and prediction shows that higher the braid length under compression, higher the change in angle. Since the above table shows that the braid length change under compression for second layer is higher than that of the first layer, the change in angle should be higher. This was also observed in Figure 44 and Figure 45.
The change in angle was only recorded around the bending curve and the effect was negligible on the tangent sides. This observation indicates that the fibre shearing under tension and compression mostly accommodates the change in parameters within the bending curve region.

Figure 44 After bending a preform braided on a 25.4 mm diameter mandrel, at compression side, braid angle increased and reached to the highest angle at the centre of the curvature, and vice versa. The braid angle of double layers braids increased more rapidly than single layer braids at compression side but decreased slower than single layer braids.
Figure 45 When a preform braided on a 12.7 mm diameter mandrel was bent, the change of braid angle was similar to 25.4 mm diameter mandrel bent. But braid angle changed more gradually from edges to the centre.

The data collected from one 25.4 mm diameter single layer braided mandrel (#1) was shown in Figure 44. Before bending, braid angle was ±45° at any point on the tube. After bending to 90°, the average braid angle at compression increased and that at tension side decreased. After bending to 180°, the greater degree of bending made
the angle change more obvious. The minimum braid angle referred to braid angle at the centre of the tension side. Similarly, the maximum braid angle means the braid angle at the centre of compression side.

Figure 46 Figure showing the maximum braid angle at compression side and minimum braid angle at tension side for a single layer braid after bending at 90° and 180°. The braid angles are collected from the centre of the curvature. Predicted braid angle were predicted by using equation 21 illustrated in Chapter 4.2
5.8. Conclusions

Preforms could be bent to desired shape before composite manufacturing. During the bending process two types of forces are applied on the braided tube—tension and compression. Braid angle was decreased after bending on tension side of the braided tube. On the other hand, the compression load led to braid angle increasing. The change in braid angle and braid diameter after bending was similarly as linear compression and tension applied on sleeves. So the braid angle and braid diameter could be predicted by equations in Chapter 4. The predicted angle and diameter did not exactly match the experimental results because the equation was built based on the assumption that the braid unit cell acts as a trellis. In fact, fibre tows slippage happened during fibre shearing as well as friction resistance played a role in the change.

After bending, at tension side, braid angle and braid diameter decreased gradually from two edges to the centre. The lowest value was collected at the centre of the bent arc. As for compression side, the highest braid angle and diameter were recorded at the centre of the curvature. The change in braid angle changed other parameters such as tow width, length of braid unit cell which eventually changed the local fibre density. That the increase in local fibre density and bulk as well as braid diameter can result in wrinkle formation at compression side as noticed in the microscopic analysis of the composite tube cross-section. To prevent such increase in local fibre density due to increase in braid angle, methods that could generate a suitable braid angle will be discussed in Chapter 6.
6. Methods for Local Braid Angle Change

6.1. Introduction

As braid angle change was observed after bending as analysed in Chapter 5, in order to accommodate the change of braid angle that occurs during bending, a local change in braid angle is required. In the compression side the angle was increased from that of the neutral axis. To prevent increase in angle thus increase in thickness, before bending a lower angle than neutral axis is required at compression side. By changing the take-up speed or rotational speed of the process, change in braid angle is possible to achieve. However, this change in angle only appears along the length of the mandrel and not localised to compression side. The effect of bending on braid parameters showed that the change in braid angle occurs in the circumferential direction of the mandrel. Hence, an alternative approach of using elliptical ring and off-centre braiding were taken to achieve local change in braid angle in the circumferential direction.

6.2. Change in shape of braid ring

An Elliptical braid ring was used in this study to investigate the effect of elliptical braid ring on braid parameters as well as change the braid angle at compression side to prevent the increase in braid thickness and angle after bending. By using both a circular and an elliptical braid ring ±45° braid structures were produced.
Use of circular braid ring is a universally used approach for braiding process. Generally, the mandrel was mounted at the centre of the braiding machine. The standard circular braid ring can ensure that the distance from bobbins to the point on the braid ring and from braid ring point to fell point are all constant, so that the braid angle could keep constant in all directions on the mandrel. In this case, the changes in rotation speed as well as take-up speed could only change the fibre orientation along longitudinal direction. But the fibre orientation remains the same around circumferential direction. Hence, if the braid ring is not circular shape, then the distance from the point on the braid ring to fell point will be changed, which will result in different braid angle around the circumferential direction. In order to achieve that, non-circular braid ring- elliptical braid ring was used in this study. Elliptical braid ring has two minor diameters and two major diameters on opposite sides. The gradual change in diameter resulted in gradual change in braid angle around the circumference direction. Elliptical braid ring that was used in this study
has 300 mm in major diameter and 150 mm in minor diameter as shown in Figure 47. The circular braid ring with 300 mm diameter was also used for comparison.

6.2.1. Braiding

The circular braid ring was mounted at the centre of the machine and the convergence length, rotation speed and take-up speed are shown in the Table 4. Once braiding was finished, the elliptical braid ring was mounted on the braiding machine (Figure 48).

Table 4 Braiding process parameters

<table>
<thead>
<tr>
<th></th>
<th>Circular braid ring</th>
<th>Elliptical braid ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Convergence length (mm)</td>
<td>100</td>
<td>75</td>
</tr>
<tr>
<td>Take up speed, v (machine setting) (mm/s)</td>
<td>8</td>
<td>9.8</td>
</tr>
<tr>
<td>Distance between ring and eyelet (mm)</td>
<td>65</td>
<td>100</td>
</tr>
<tr>
<td>Braid angle located along the vertical plane of the ring (along minor dia of the elliptical ring) (°)</td>
<td>±45</td>
<td>±45</td>
</tr>
<tr>
<td>Braid angle located along the horizontal plane of the ring (along major dia of the elliptical ring) (°)</td>
<td>±45</td>
<td>±41</td>
</tr>
</tbody>
</table>

The elliptical braid ring was set at the same position as the circular braid ring. According to the braid angle calculation equation, in order to create ±45° structure braid, bobbins rotation speed and take-up speed could be input into the system as following (Table 4).
The braid angle of ±45° could be located along two minor diameters sides. The braid angle at two major diameter sides was less than ±45°. Therefore, major diameter corresponds to small braid angle, and vice versa. By using an elliptical braid ring (Figure 48) different braid angles at its major (β) and minor diameter (α) was
produced where $\beta<\alpha$. The braid angle appears to be the same at opposing quadrants around the core (Table 5).

Table 5 Braid angle are the same at opposing quadrants around the mandrel

<table>
<thead>
<tr>
<th>Position around mandrel ($^\circ$)</th>
<th>Braid angle ($^\circ$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$\pm 41$ ($\beta$)</td>
</tr>
<tr>
<td>90</td>
<td>$\pm 45$ ($\alpha$)</td>
</tr>
<tr>
<td>180</td>
<td>$\pm 41$ ($\beta$)</td>
</tr>
<tr>
<td>270</td>
<td>$\pm 45$ ($\alpha$)</td>
</tr>
</tbody>
</table>

By using elliptical braid ring rather than standard ring in braiding process, braid angle formation before bending were shown in Table 5. Braid angle at two opposite sides of the mandrel kept $\pm 45^\circ$. But at the other two sides, braid angle became lower, only $\pm 41^\circ$. It is caused by change of radius of braid ring.

After braiding, take-off the mandrels and put them on the die of the bending machine for bending. The same bending process was used here to bend the tube to $90^\circ$ and $180^\circ$. Owing to the fact that the elliptical braid ring have two major diameters and two minor diameters, which resulted in different braid angle around the circumference. Besides, after bending process, the braid angle at compression side increases and angle decreases at the tension side, the angle at the other two sides keep constant. So one of small braid angle side was placed at the compression side and the other small braid angle side was tension side during bending. Hence, braid angle of $\pm 45^\circ$ was kept constant after bending. One side of large braid angle could increase to nearly $\pm 45^\circ$. Thus, braid angle at three sides of the tube could be same.
6.2.2. Limitation of elliptical braid ring in maypole braider

Braid angle has a wide range while braiding using circular braid ring. However, when braided using elliptical braid ring, high angle braid could not be braided because the convergence length for a high angle braid was too small to be in contact with the braid ring. This is a limitation in maypole braider. So during braiding process, elliptical braid ring will play a role in locally braid angle change only when all of the fibre tows touch the braid ring.

<table>
<thead>
<tr>
<th>Braid angle (°)</th>
<th>Distance from fell point to eyelet (mm)</th>
<th>Feasibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>±30°</td>
<td>225</td>
<td>Yes</td>
</tr>
<tr>
<td>±45°</td>
<td>200</td>
<td>Yes</td>
</tr>
<tr>
<td>±60°</td>
<td>135</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 6 Effect of convergence length on braid feasibility

6.3. Change in the position of the core

In standard braiding machine setting, the mandrel is set at the centre of the machine to ensure the position of mandrel would not affect the fibre orientation. However, this study aims to change the fibre orientation. So changing the position of the mandrel would definitely change the braid angle formation. In order to set the mandrel away from the centre, an aluminium plate with some holes (Figure 49) was used in this study. The mandrel could be set even distance from the centre.
Figure 49 Image of plate used for mandrel off-centre setting

Figure 50 Schematic of the front view of a braiding machine. Horizontal plane off-centre location of the mandrel is shown with respect to braid ring. Four measurement positions on the mandrel are shown in anti-clockwise direction.

In this part of the study, mandrels were mounted on the take-up device at off-centre position of the whole machine and four points of mandrel are pointed out in Figure
50. The braiding process was following the process that was discussed in section 3.2.3.

6.3.1. Relation between carrier compensation length and off-centre braiding

As it was illustrated in Section 2.5 that when the carrier moves from the furthest point to the nearest point, an extra length was created during braiding which led to extra fibre tow on uneven braid surface. In the literature [34], the compensation length was studied and the length from eyelet to braid ring could be calculated by equation 7. In this study, more compensation length was needed because an extra length was created by braid ring off-centre setting. The difference in length from braid ring to fell point could also be calculated as follow.

\[ \Delta P = P_2 - P_1 = \sqrt{(R + f)^2 + c^2} - \sqrt{(R - f)^2 + c^2} \]  

Figure 51 Schematic of circumferential braiding compensation length variation between braid ring and braid point. (left) side view. (right) top view
Where $\Delta P$ is the difference between $P_1$ and $P_2$; $P_1$ is the nearest distance from braid ring contact point to fell point; $P_2$ is the furthest distance from braid ring contact point to fell point; $R$ is the radius of braid ring; $f$ is the horizontal distance from mandrel centre line to machine centre line; $c$ is convergence length.

Owing to the fact that the total compensation length required during braiding is the maximum differences from eyelet to fell point, so

$$\Delta C = \Delta lc + \Delta P \quad \text{(28)}$$

Where $\Delta C$ is the compensation length that required during braiding.

Substituting equation (7) and (27) into equation (28) yields the maximum compensation length.

$$\Delta C = \sqrt{(h_1 + h_2)^2 + d^2} - \sqrt{h_1^2 + d^2 + (R + f)^2 + c^2} - \sqrt{(R - f)^2 + c^2} \quad \text{(29)}$$

### 6.3.2. Limitation of off-centre braiding

The parameters $h_1$, $h_2$, $d$, $R$, $f$ and $c$ was measured by using measuring tape. Substituting $h_1$, $h_2$, $d$, $R$, $f$ and $c$ into equation (29), the compensation length from eyelet to braid ring ($\Delta lc$) and distance from braid ring to braid point ($\Delta P$) can be calculated. Also, the total compensation length that is required during braiding ($\Delta C$) can be calculated (shown in Figure 52).
Figure 52 Factors affecting the required compensation length during braiding. (a) Original setting is setting the distance between a braid ring and the eyelet to 100 mm with braid ring radius 100 mm and convergence length 110 mm. (b) (c) (d) When the mandrel was set 50 mm off-centre, the increase in the distance between braid ring and carrier eyelet, braid ring radius and convergence length (lower braid angle) resulted in more compensation length was required.

As it was shown in Figure 52, the distance from mandrel centre line to machine centre line (f), the horizontal distance from braid ring to eyelet (d), braid ring radius (R) and convergence length were all played an important role on compensation length required during braiding process. Equation 29 and Figure 52 showed the relation between compensation length and these factors. As h₁ and h₂ were unchangeable, the compensation length (∆C) was proportional to the distance from mandrel centre line to machine centre line (f) and braid ring radius (R) but was
inversely proportional to the distance from braid ring to eyelet (d) and convergence length (c).

The maximum compensation length that maypole braiding machine used in this study could give was measured from the machine, which was 210 mm. Keeping the fibre tow on the compensator roller, fibre tow was pulled until the bobbin started to rotate. This was the point at the compensator roller reached to its maximum limit. The length of the fibre tow that was pulling out is the maximum compensation length of the maypole braiding machine. So \( \Delta C \) should be no more than 210 mm.

6.3.3. Braiding with off-centre setting

In this study, a circular braid ring with 150 mm radius was set 100 mm away from the eyelet. Convergence length was 110 mm to produce braid structure of \( \pm 45^\circ \) braid angle. According to Figure 52, the maximum distance that the mandrel could move away from the centre was 50 mm. Because of the limitation of maypole braiding machine’s compensation length, when mandrel was set more than 50 mm away from the centre, fibre tows were loose and that led to braid angle distortion. On the other hands, structure of \( \pm 60^\circ \) could not be produced because fibre tow did not touch the braid ring. In this study, the mandrel was set 6 mm, 12.5 mm, 25 mm, 37.5 mm, 50 mm, 62.5 mm and 100 mm away from the centre. The setting up data was shown in the Table 7.
Table 7 Data setting for off-centre braiding

<table>
<thead>
<tr>
<th>Mandrel axis off set (mm)</th>
<th>Setup for Braid angle (°)</th>
<th>Actual convergence length (mm)</th>
<th>Feasibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>±45</td>
<td>110</td>
<td>Yes</td>
</tr>
<tr>
<td>12.5</td>
<td>±45</td>
<td>110</td>
<td>Yes</td>
</tr>
<tr>
<td>25</td>
<td>±45</td>
<td>110</td>
<td>Yes</td>
</tr>
<tr>
<td>37.5</td>
<td>±45</td>
<td>110</td>
<td>Yes</td>
</tr>
<tr>
<td>50</td>
<td>±45</td>
<td>110</td>
<td>Yes</td>
</tr>
<tr>
<td>62.5</td>
<td>±45</td>
<td>110</td>
<td>Yes</td>
</tr>
<tr>
<td>100</td>
<td>±45</td>
<td>N/A</td>
<td>No</td>
</tr>
</tbody>
</table>

When the mandrel moved from centre to 6 mm, 12.5 mm, 25 mm, 37.5 mm and 50 mm away from the machine centre, the required compensation length was less than 210 mm. However, when the mandrel was 62.5 mm away from the machine centre, the required compensation length was 220 mm, which was 10 mm higher than machine’s compensation length. This small difference was not reflected in the braid. But fibre slack was observed during braiding (shown in Figure 53)

Figure 53 Fibre loosed when mandrel was set 62.5 mm away from the machine centre
Figure 54 Effect of compensation limitation in braiding process. Mandrel was set 100 mm off-centre (a) front view of fibre slack (b) fibre slack during braiding (c) fibre hoop was created because of slack fibre tow (d) convergence length various due to fell point moving (e) fibre tow out of guide causing fibre damage

In order to see the effect of limitation of compensation length on braids, the mandrel was set 100 mm away from the machine centre. When the required compensation length was 64 mm, which was longer than machine’s ability, fibre hoop was created, fell point moved and severe fibre loose was observed (Figure 54).

6.3.4. Effect of core position on braid parameters

Fibre orientation could become variety in terms of the position of the core. Considering the mandrel was moved towards 180° direction, the distances from the
fell point to the contact point between fibre tow and braid ring were different at four
directions. At 180°, it was smaller than that at 90° or 270° which were equal. But for
0°, it had the longest distance.

Figure 55 Comparing braid angle (maximum and minimum) before bending and
after bending to 180° (12.5 mm offset). The dotted line indicates braid angle at the
neutral axis.

As shown in Figure 55, before bending, the smallest distance corresponds to the
maximum angle and vice versa. The braid angle at 90° and 270° were ±45°. The
braid angle at 0° was ±42°, but at 180°, it was ±47°. Bending process could be
carried out by keeping 90° and 270° as neutral axis. In this case, ±45° would keep
constant. Based on the effect of bending on braid angle distribution as discussed in
Chapter 5, 180° side should be kept under tension side so that braid angle could
decrease to ±42° and then reduce the chance to form wrinkle. At 0°, the lowest angle could increase to ±49°.

Table 8 showed braid angle change after bending when mandrel moved 12.5 mm, 25 mm, 37.5 mm and 50 mm away from the machine centre respectively. Before bending, braid angle at 0° slightly reduced but slightly increased at 180° while mandrel moving further. But after bending, braid angle changed more at 0° but moved less at 180° when mandrel moved further. Besides, braid angle changed more at compression side than tension side.
<table>
<thead>
<tr>
<th>12.5 mm off centre</th>
<th>Before bending</th>
<th>After bending to 90°</th>
<th>Change in angle after bending</th>
<th>After bending to 180°</th>
<th>Change in angle after bending</th>
</tr>
</thead>
<tbody>
<tr>
<td>Braid angle at 0°</td>
<td>42</td>
<td>46</td>
<td>4</td>
<td>49</td>
<td>7</td>
</tr>
<tr>
<td>Braid angle at 180°</td>
<td>47</td>
<td>42</td>
<td>-5</td>
<td>40</td>
<td>-7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>25 mm off centre</th>
<th>Before bending</th>
<th>After bending to 90°</th>
<th>Change in angle after bending</th>
<th>After bending to 180°</th>
<th>Change in angle after bending</th>
</tr>
</thead>
<tbody>
<tr>
<td>Braid angle at 0°</td>
<td>41</td>
<td>47</td>
<td>6</td>
<td>49</td>
<td>8</td>
</tr>
<tr>
<td>Braid angle at 180°</td>
<td>48</td>
<td>44</td>
<td>-4</td>
<td>42</td>
<td>-6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>37.5 mm off centre</th>
<th>Before bending</th>
<th>After bending to 90°</th>
<th>Change in angle after bending</th>
<th>After bending to 180°</th>
<th>Change in angle after bending</th>
</tr>
</thead>
<tbody>
<tr>
<td>Braid angle at 0°</td>
<td>41</td>
<td>48</td>
<td>7</td>
<td>50</td>
<td>9</td>
</tr>
<tr>
<td>Braid angle at 180°</td>
<td>48</td>
<td>46</td>
<td>-2</td>
<td>44</td>
<td>-4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>50 mm off centre</th>
<th>Before bending</th>
<th>After bending to 90°</th>
<th>Change in angle after bending</th>
<th>After bending to 180°</th>
<th>Change in angle after bending</th>
</tr>
</thead>
<tbody>
<tr>
<td>Braid angle at 0°</td>
<td>41</td>
<td>48</td>
<td>7</td>
<td>50</td>
<td>9</td>
</tr>
<tr>
<td>Braid angle at 180°</td>
<td>49</td>
<td>47</td>
<td>-2</td>
<td>45</td>
<td>-4</td>
</tr>
</tbody>
</table>
6.4. Conclusions

Elliptical braid ring could achieve the braid angle vary around circumferential direction. Braid angles were the same on adjacent sides. After bending, one side with lower braid angle increased to nearly the same as the angle on neutral axis. In that case, braid angle at three sides became same or nearly same after bending, especially preventing the braid angle to increase more than that of neutral axis in the compression side. However, the braid angle on opposite side became lower than the angle braided. Also, instead of producing a ±45°, if a larger braid angle is required using a maypole braider, the elliptical ring concept may not be useful. This is due to the small convergence length which will result in the fibres not touching the braid ring and thus no effect of ellipticity will be reflected on the braid angle.

The mandrel was set off-centre only at horizontal plane of the circular braid ring and braid angle at two opposite sides were same. The other two opposite sides had two different braid angles unlike the elliptical ring study. The angles were lower and higher than that of the other set of the same braid angles. During bending, the highest braid angle was kept at tension side and the lowest braid angle was kept at compression side. The angle at compression and tension side changed to nearly the same as neutral axis for certain off-centre distance and degree of bending. However in most cases the change in angle was larger than that at the neutral axis which is not suitable to consider bending as the local fibre density will change similarly like a concentric braided mandel leaving the possibility of wrinkle formation. Thus, appropriate selection of off-centre distance and elliptical ring diameter can
effectively achieve desired braid angle locally to minimise prospect of wrinkle formation.

In addition, during off-centre braiding, the limitation of carrier compensation length was studied. The total compensation length could be calculated so that the braid feasibility could be predicted. In this study, the maximum distance between mandrel centre line and machine centre line was 50 mm. The increase in distance from mandrel centre line to machine centre line and the braid ring radius resulted in an increase in compensation length. On the other hand, the compensation length could also increase when braid ring was close to the machine and reduced the convergence length. According to the equation, it could be predicted that when the mandrel was 62.5 mm off centre setting, the required compensation length was higher than that of the carrier capacity. If the mandrel was moved further, several slack fibres were observed which eventually damaged some fibre tows. Thus, before selecting an off-centre distance the total compensation length should be predicted to keep it within the carrier’s capacity to prevent fibre damage.
7. Analysis and Discussions

7.1. Effect of linear compression and linear tension on braided preforms

The experiments in this study show that if a braided mandrel is subjected to bending, change in braid geometry around the cross-section of the bent section was observed. After bending, the reduction of length at inner curvature leads to increasing on braid angle and diameter. The length increase under tension leads to braid angle and diameter decrease. Linear compression and linear tension have similar effect as bending. So earlier in this study, the effect of linear compression and linear tension were studied in order to find out the relationship between the change in length and the change in braid angle as well as diameter under loading. It was found that when initial braid angle was ±45°, the diameter was 26.6 mm. As the compression force was applied further, the locking braid angle was reached and it was ±66°. Beyond this point, wrinkle formation was observed. But in standard braiding case, braid angle could reach to ±51° maximum. So wrinkle was not observed at this stage however, during composite manufacturing, under vacuum condition, due to the consolidation force, the wrinkle was formed at compression side where the braid angle was ±51°. Based on linear compression and tension equation, the decrease in length resulted in the increase in braid angle. When the braided tube was bent to 180°, the length of inner arc and outer arc were 559 mm and 641 mm respectively which changed from the neutral axis length of 600 mm. By using the equation,
the predicted braid angles were $\pm 49^\circ$ and $\pm 41^\circ$ at compression and tension side respectively. However, the experimental value discussed in Chapter 5 shows that the maximum braid angle at compression side was $\pm 51^\circ$ and the minimum braid angle at tension side was $\pm 42^\circ$. The difference between predicted braid angle and experimental angle was because the equation was derived based on the simulation that the four sides of the unit cell remain equal during compression or tension. Also, the four points at the boundary of the unit cell acts as pivots to form a trellis changing the position under compression or tension without any resistance or slippage. The experimental results matched to predicted value quite well.

7.2. **Effect of bending on braided preforms**

Then standard bending (mandrels were braided by using circular braid ring) were carried out to investigate how the braid angle change after bending at compression side, tension side and neutral axis. In order to accommodate the change in the braid angle occurring during the bending, a local variation of the braid angle is required. Change in braid angle is possible to be achieved by changing the rotational speed of carriers or linear speed of the process. However this change in angle only appears along the length of the mandrel. According to the effect of bending on the braiding parameters, it indicates that the change in the braid angle occurs in the circumferential direction of the core. Hence, a non-circular braid ring is an effectively method to change the braid angle locally around its circumference direction. Thus, in order to change the braid angle locally, two methods were used to achieve that. One is using a non-circular braid ring instead of the circular braid ring. In this study, elliptical braid ring was used to change the fibre orientation around the
circumference direction. The other one is changing the position of the mandrel by moving the mandrel away from the centre.

Bending was carried out by keeping the quadrants with ±45° braid angle along the neutral axis. After bending, braid angle at neutral axis remained the same. After mandrel bending to 90°, braid angle at tension side decreased but increased at compression side. However, at neutral axis, braid angle kept constant because there is no force applied along neutral axis. As for bending to 180°, braid angle changed more than before.

![Figure 56 Change in braid angle (maximum and minimum) after bending (elliptical braid ring)](image)

The braid angle at compression side changed from ±40° to about ±45°. This change in angle led the braid angle at compression side to be the same as that at the neutral axis.
axis. This change in angle to \( \pm 45^\circ \) at compression side is desirable as it will prevent the increase in braid density by increasing braid angle and eventually prevent the possibility wrinkle generation during vacuum bagging.

Table 9 The maximum braid angle (°) at compression side after bending

<table>
<thead>
<tr>
<th>Ring type</th>
<th>Before bending</th>
<th>After bending (90°)</th>
<th>After bending (180°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circular ring</td>
<td>45</td>
<td>51</td>
<td>54</td>
</tr>
<tr>
<td>Elliptical ring</td>
<td>41</td>
<td>44</td>
<td>45</td>
</tr>
</tbody>
</table>

The maximum angle at the centre of the compression curvature was recorded in the Table 9. This change in angle to \( \pm 45^\circ \) at compression side is desirable as it will prevent the increase in braid density by increasing braid angle and eventually prevent the possibility wrinkle generation during vacuum bagging.

7.3. Effect of shape of braid ring (elliptical braid ring)

In tension side, as braid angle decreased after bending, which would not lead to wrinkle forming, only change at compression side were taken into account. After bending to 180°, while braiding by using circular braid ring, braid angle increase from \( \pm 45^\circ \) to nearly \( \pm 52^\circ \). Wrinkle formation was observed after resin infusion. As for braiding using elliptical braid ring, the initial angle was \( \pm 41^\circ \). After bending, it reached to nearly \( \pm 45^\circ \). As the larger the angle, the greater the likelihood of the formation of wrinkles, elliptical ring reduced the chance to form wrinkle.
7.4. Effect of off-centre setting of the braid ring

Changing the shape of braid ring is an effective method to change the braid angle locally. But after bending, braid angle at tension side, which was lower than braid angle at neutral axis, became even lower. Hence, another method of changing the position of mandrel (offset) can be used to optimise the braid angle locally as well. In this way, the braid angle at the tension side can be developed to be higher than that at neutral axis. As a result, under tension it can decrease to the angle similar to that of neutral axis avoiding major change as observed with elliptical or circular ring braid after bending.

However, in most cases, the change in angle was greater than that at the neutral axis, which is not suitable for bending due to the local fibre density will change similarly like a concentric braided mandel leaving the possibility of wrinkle formation. Thus, appropriate selection of off-centre can effectively achieve desired braid angle locally, thereby minimising prospect of wrinkle formation.

7.5. Wrinkle formation after resin infusion

The change in fibre orientation was observed when linear over-braided cylindrical cores were subjected to be bent to 90° and 180°. Braid parameters changed due to tension and compression force applied on the bent section during bending. Increase in braid angle and increase in thickness can potentially lead to wrinkle generation. As discussed above, elliptical braid ring can effectively change the braid angle around the circumference direction. Braid angle at inner bent section is smaller than the angle at neutral axis. Thus, after bending, braid angle increased, but it was still...
lower than preform braided by using circular braid ring. Different braid angle had an effect on thickness. Figure 57 shows wrinkles were eliminated by braiding using elliptical braid ring instead of circular braid ring. Table 10 and Table 11 showed that higher braid angle led to thicker wall thickness. Once the braid angle increased to a certain degree (e.g. locking angle), wrinkle was created.

Figure 57 Half piece of composite tubes for observation of wall thickness (a) Wall thickness variation with small wrinkles are observed for composite, the preform of this composite was braided by using circular braid ring where the braid angle changed at the compression side to ±54° from ±45° at neutral axis. (b) Uniform wall thickness at compression side of the tube and the preform of this tube was braided by using elliptical braid ring where the angle changed to ±45° at compression side after bending from ±41° before bending
Table 10 The minimum braid angle at tension and the maximum braid angle at compression side after bending to 180°

<table>
<thead>
<tr>
<th>Ring type</th>
<th>After bending (180°)</th>
<th>After bending (180°)</th>
<th>Along neutral axis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tension side</td>
<td>Compression side</td>
<td></td>
</tr>
<tr>
<td>Circular ring</td>
<td>38</td>
<td>54</td>
<td>44.9</td>
</tr>
<tr>
<td>Elliptical ring</td>
<td>36</td>
<td>45</td>
<td>45</td>
</tr>
</tbody>
</table>

Table 11 Mean average thickness (mm) at tension and compression side after resin infusion

<table>
<thead>
<tr>
<th>Ring type</th>
<th>After bending (180°)</th>
<th>After bending (180°)</th>
<th>Along neutral axis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tension side</td>
<td>Compression side</td>
<td></td>
</tr>
<tr>
<td>Circular ring</td>
<td>0.80</td>
<td>1.27</td>
<td>0.86</td>
</tr>
<tr>
<td>Elliptical ring</td>
<td>0.69</td>
<td>0.85</td>
<td>0.75</td>
</tr>
</tbody>
</table>

The thickness showed a large variation on compression side because of wrinkle with small amplitudes. As shown in Figure 58(a), the maximum wrinkle amplitude is 1.82 mm. But no wrinkle was shown in Figure 58(b), the maximum thickness is 0.87 mm. Therefore, wrinkle was eliminated by using elliptical braid ring instead of circular braid ring.
Braid angle could be changed locally by using these two methods. As a result, after bending, the increase in braid angle would be no longer reach to locking angle. Hence, wrinkle formation could be eliminated.

7.6. Conclusions

This chapter illustrated the summarised results and analysis. Change in shape (bending) resulted in braid angle formation change around circumferential direction. Tension and compression force were applied on two opposite sides of tube. As higher braid angle caused wrinkle, two methods were used to optimise the braid angle. Elliptical braid ring and mandrel off-centre setting were used in this study to potentially mitigate wrinkle formation. Two different braid angles were produced on two adjacent sides of a mandrel by using elliptical braid ring. After bending, the
braid angle at neutral axis kept constant. On compression side, the braid angle increased to be close to the braid angle at neutral side. However, the lower braid angle at tension became lower than the initial angle. So another method of setting the mandrel off-centre was studied using circular ring. In this case, three different braid angles were produced around a manrel circumference after braiding. Two of these angles were ±45° and these were kept at the neutral axis during bending. The other two angles was higher and lower than ±45°. The lower braid angle and higher braid angle were kept at compression side and tension side respectively. Thus after bending at 90°, the lower braid angle and the higher braid angle tended to be as the same as neutral axis for 25 mm offset. Then wrinkle could be prevented being forming after bending. As in other off centre settings, the change in angle was larger than that at the neutral axis, the off-centre distance needs to be selected carefully to prevent the angle change higher than desired.
8. Conclusions and Future Work

Composites manufactured using braided preform can generate defects due to out of plane deformations such as wrinkles during the vacuum assisted resin infusion methods. Fibre orientation, which is a very important parameter for composite mechanical properties, can change due to the shape change. This study introduced two methods to change the braid angle on preforms to lead to an improvement of wrinkle formation on bent composite tube. Wrinkles can get generated in composite tubes around its circumferential direction while forming of complex shapes with a high degree of bending. Because the curvature section is subjected to tension and compression during bending, this influence the braid angle to change by fibre shearing.

Considering the deformation of a braid unit cell is similar to that of a trellis, a method for predicting the angle changes was presented. Braid angles and diameter data were collected after braid being loaded under uniaxial tension as well as compression. Predicted braid angle showed a good correlation with the practical measurement until the shear locking limit was reached. Once the braid angle reached to shear locking limit, no change in the braid angle and diameter was recorded with additional force and deformation.

To study the effect of bending on the braided parameters, over-braided cores were bent to 90° and 180°. The minimum and maximum braid angle values at the curve centre were increased and decreased at the compression side (inner bend) and tension side (outer bend) respectively. As no load applied along the neutral axis, the braid angle remained constant. Along the bending curve a gradual change in braid angle
was observed from the edge of the tangent to the centre of the bending curve. On the compression side, the maximum angle was observed at the centre of the bending arc and the decrease in angle on the tension side was observed with the lowest angle located at the centre of the bending curve. In compression side, the increase in braid angle of outer layer was higher than first layer because more decrease in length result in higher braid angle. On the contrary, in tension side, the braid angle after bending showed a more significant increase at first layer. It is probably because the increase in tension at outer layer eventually increases the friction resistance, which is likely to play a role in smaller change in braid angle.

Localised change in braid angle around the circumference was achieved by using an elliptical braid ring. The elliptical ring generated two different braid angles along major and minor axis and the angles at the opposing quadrants of the braid circumference were equal. Based on the change regulation in braid angle, during bending at compression side, braiding was carried out to produce ±45° and ±41° using the elliptical ring. After bending, braid angle at neutral axis remain same and hence ±45° angles were kept at the neutral axis. The braid angle at compression side changed from ±41° to about ±45°. This change in angle leads the braid angle at compression side to be the same as that at the neutral axis. The local angle variation improves the angular consistency around the circumference as compared to the braid produced using a circular ring. Circular ring generated the same angle around the core and the after bending the angle changed to about ±42° and ±51° at tension and compression side respectively. Thus, the occurrence of wrinkle formation can be minimised or even eliminated by changing the angles locally and using the advantages of the deformation of parameters of the braid.
Localised braid angle change in circumferential direction was also completed by off-centre setting of the braid ring. The difference in distance from eyelet to fell point led to various distribution of braid angle. Two opposite sides with same braid angle ($\pm 45^\circ$) were kept at neutral axis. Unlike the effect of elliptical braid ring, other two opposite sides on the mandrel had two different braid angles. One side had a higher and the other one side had a lower braid angle than $\pm 45^\circ$. The highest braid angle side was kept as tension side so that it reduced after bending. Similarly, the lowest braid angle was kept at compression side and the angle increased under compression load. Thus, braid angle tended to be same after bending for 25 mm offset and for 90° bending. The change in braid angle was not significant for different off-centre distances however the change in braid angle after bending was noticeable. Between the specimens the braid density (tows per cm) was observed to be different and this difference contributed to the change in angle after bending.

The compensation length is an important factor that should be taken into account for off-centre braiding. The total required compensation length should not be more than the compensation length that could be provided by machine. The mandrel could not be moved further away from the centre because of the limitation of compensation length.

Some further studies that could be done in the future are as follows:

1. Multi-layers preforms could be braided to investigate the effect of the number of layers on wrinkle formation.

2. Composite mechanical testing could be done to study the impact of wrinkle on mechanical properties as well as effect of change in braid angle on overall mechanical properties as well as failure mechanism.
9. Bibliography


57. Toray carbon fibres america, i., *Torayca T700S data sheet*.


