Influence of Bending on Wrinkle Formation and Potential Methods of Mitigation

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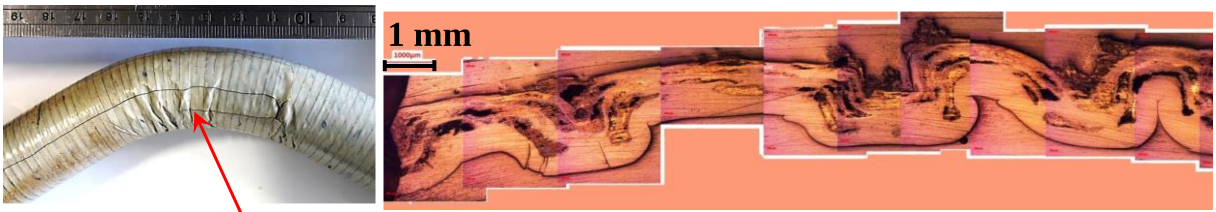
ABSTRACT

The study investigates wrinkle formation during bending of the braided composite tube. Consolidation of the preform and change in braid parameters due to fibre scissoring were found to be two major influencing factors for causing out-of-plane deformation. The change in braid angle and diameter under uniaxial tension and compression loading were studied and a prediction method was devised. Bending of over-braided preform showed substantial change in braid angle around the circumference as well as along the length. Optimisation of braid parameters was carried out by changing the braid angle locally around the circumference of the braid in order to compensate for the distortion during bending. The braid angle measured after bending the optimised structure showed improvement that can eliminate one of the factors influencing the out-of-plane deformation thus wrinkle generation.

1 INTRODUCTION

The application of composite pipes and tubes are increasing gradually due to high specific strength and stiffness properties. Also, one of the major advantages is reduced number of parts, fasteners and connectors for pipes as complex shaped components can be manufactured using textile reinforcements. For composite tubes and pipes, filament winding is the most widely used manufacturing methods. However, the use of braiding[1] is becoming widespread in the industry due to its high production rate as well as mechanical performance.



(a)
Wrinkle at compression side

(b)

Figure 1: (a) An example of a bent braided composite tube with wall wrinkle generated during post-forming (b) Optical microscopy image of the wrinkled wall showing layer distortion

Over-braiding a linear structure is relatively simple that requires a core (also known as a mandrel) to be passed through the centre of the braiding machine. In order to manufacture non-linear shapes, there are two possible routes and these are the use of a non-linear core for over-braiding or post forming a linear preform to the desired shape. Linear over-braided cylindrical cores were subjected to 90° and 180° of bending and change in fibre orientation (braid angle) was observed during this study. The change in braid parameters occurs during bending due to tension and compression around the bent section. One of the defects such distortion in braid angle can generate is wrinkle on the composite tube (Fig. 1) and it can lead to lower mechanical properties. On the other hand, wrinkle formation is also influenced by the preform consolidation process. This article focuses on studying the change in angle and minimising the angle distortion as it is one of the factors that lead to wrinkle generation.

In a previous study, moulding a straight woven tube was carried out by placing onto a bent tubular structure that observed wrinkle formation[2]. Re-engineering the fabric by changing warp length and weft density was proposed in order to prevent wrinkle formation. Similarly, for the braided preform, the local density can be changed prior to bending at the inner and outer bend by changing braid parameters such as braid angle, tow width, braid thickness and diameter.

During bending, the length of the bent section of the tube is compression at the inner curve away from the neutral axis. The fibre rearrangement occurs due to shear deformation during compression or tension for textile preforms[3]. As the shear deformation continues under loading, braid angle continues to change until it reaches 'locking angle' limit. Once the locking limit is reached, further loading raises the propensity of out-of-plane deformation and thus formation of wrinkles at the compression side of the bent. As the wrinkle formation is related to compressive deformation of the braid structure, initially relation between changing braid angle with compressive deformation for a linear preform was established by prediction as well as experiments.

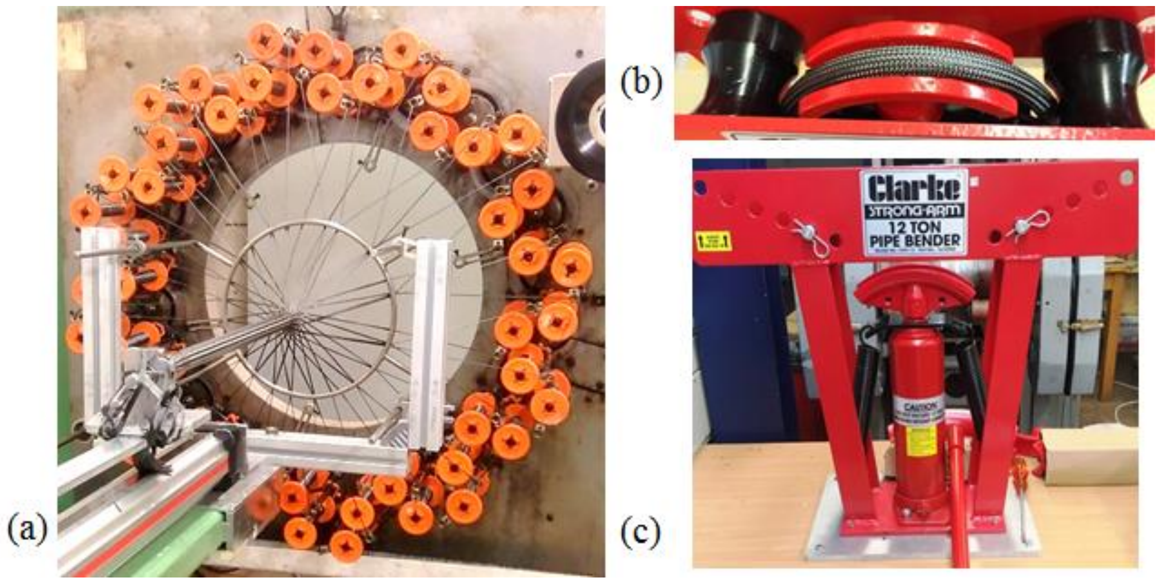


Figure 2: (a) A 48 carrier maypole braider used for over braiding (b) Top view of a carbon fibre braided core on bending equipment (c) Hydraulic bending equipment used for this study

To prevent the increasing angle at the compression side to reach the braid angle locking limit, smaller braid angle can be produced locally before bending. Such local change in braid angle was achieved by using non-circular forming ring during braiding[4]. Changing the shape of the braid ring is one of the methods that was used to study the bending effect on braid parameters. In all cases, 12k carbon fibre (T700SC) was used for braiding onto a 25-mm diameter core. A 48-carrier maypole braiding machine (Fig.2a) was used and regular (2/2) braid structures were produced. The study was carried out by bending over-braided cores at both 90° and 180° (U shape). Braiding was carried out at ±30°, ±45°and ±60° however only ±45° bending data is presented in this article.

2 EFFECTS OF COMPRESSION ON BRAIDED PREFORM PARAMETRES

The biaxial braid architecture has the inherent feature of fibre shearing under tensile and compressive force. The 'Chinese finger trap' principal of braid shows changes in braid diameter along with a change in braid angle[5]. During bending, the inside radius (R_i) of a tube is same as that of the bending die radius. This is smaller than that of the outer (R_o) and neutral axis radius (R). If the degree of bend is θ and the braid radius is r_b, the length of the braided tube at the inner curve (L_i) and outer curve (L_o) can be calculated as follows.

$$L = R\theta \quad (1)$$

$$L_i = R_i\theta = (R - r_b)\theta \quad (2)$$

$$L_o = R_o\theta = (R + r_b)\theta \quad (3)$$

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.

In order to study the effect of compression on braid angle, a ±45° braid on 25 mm core dia was compressed and the subsequent change in angle and diameter was recorded. The length of the braid loaded was selected based on the length that goes under compression and tension during bending. By using equation (2) and (3) the length of the braided tube for a 90° of bending (minimum length under compression at inner radius) was calculated to be 78.5 mm and 235.5 mm for an 180° of bending (maximum length under tension at outer radius). Hence a 200 mm long braided sleeve was loaded under compression up to 70 mm and under tension up to 240 mm. The load was applied in several steps and in each step, it was continued until 10 mm deformation is achieved and the braid structural parameters were measured.

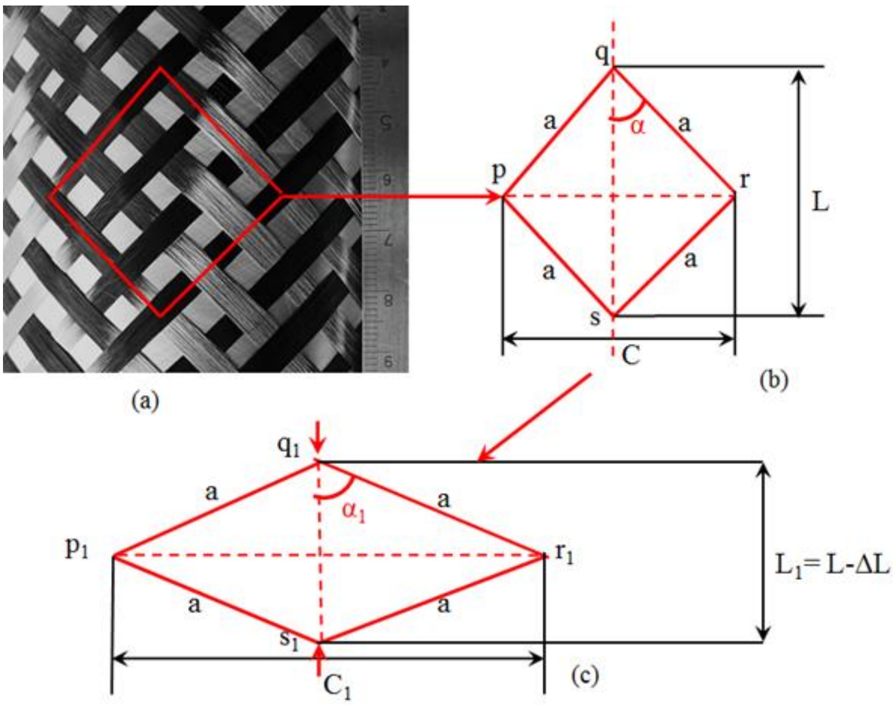


Fig 3 (a) Regular braid structure on a cylindrical core (b) Schematic diagram of a braid unit cell (c) Schematic diagram of a unit cell under compression assuming the sides are pivoted

During deformation, the braid angle and braid diameter changes as the braid unit cell shape are changed. Considering the braid unit cell acts as a trellis in which the intersecting four sides are pivoted, the braid angle and braid diameter under uniaxial load can be calculated using equation (4) and (5).

$$D_1 = \sqrt{\frac{n^2L^2}{\pi^2}(1-(1+\varepsilon)^2)+D^2} \tag{4}$$

$$\alpha_1 = \tan^{-1}\frac{\pi D_1}{nL\,(1+\varepsilon)} \tag{5}$$

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 (Fig.3b) and ε is the longitudinal strain under loading. The notations, α, α_1 and n indicate initial braid angle, braid angle after deformation and the number of unit cells around the circumference respectively.

As tension and compression force is applied to the braid, the change in braid angle and diameter was recorded. the experimental measurements were compared with the predicted angle for same unit cell length in Fig. 4d and 4e. As the braid angle increased, braid outer diameter was also increased (Fig.3d) simultaneously until 80 mm length was compressed. At this stage, the braid angle reached locking limit (about ±65°) and circumferential wrinkle appeared in the sample. Further compression up to 70 mm length, no braid angle change was observed. this observation will be correlated with the braid angle change during bending in the following section.

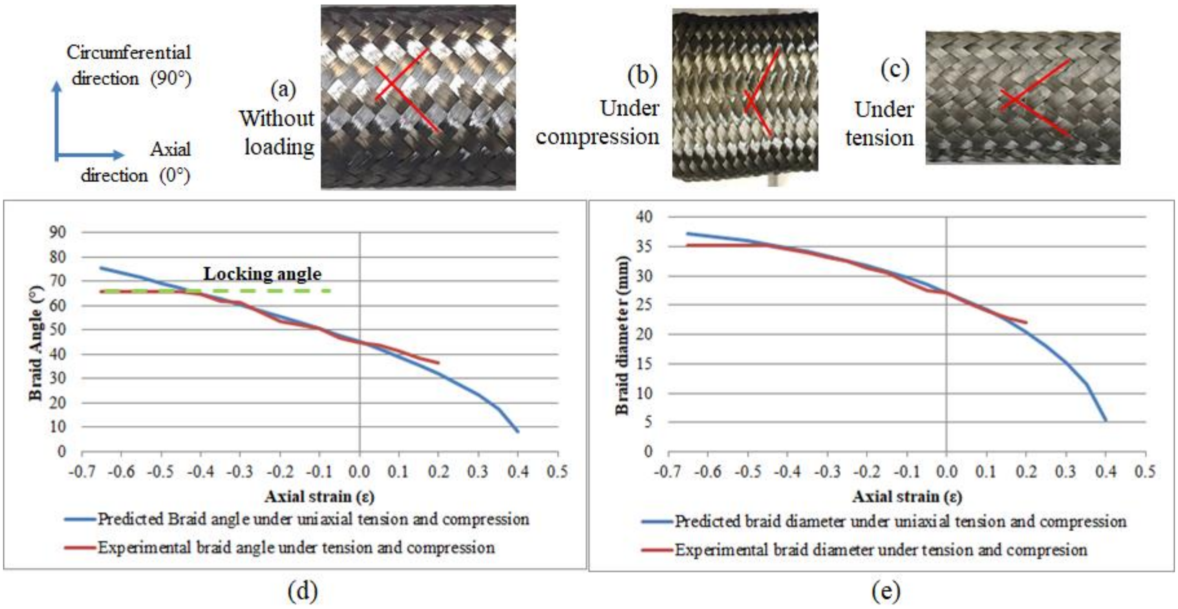


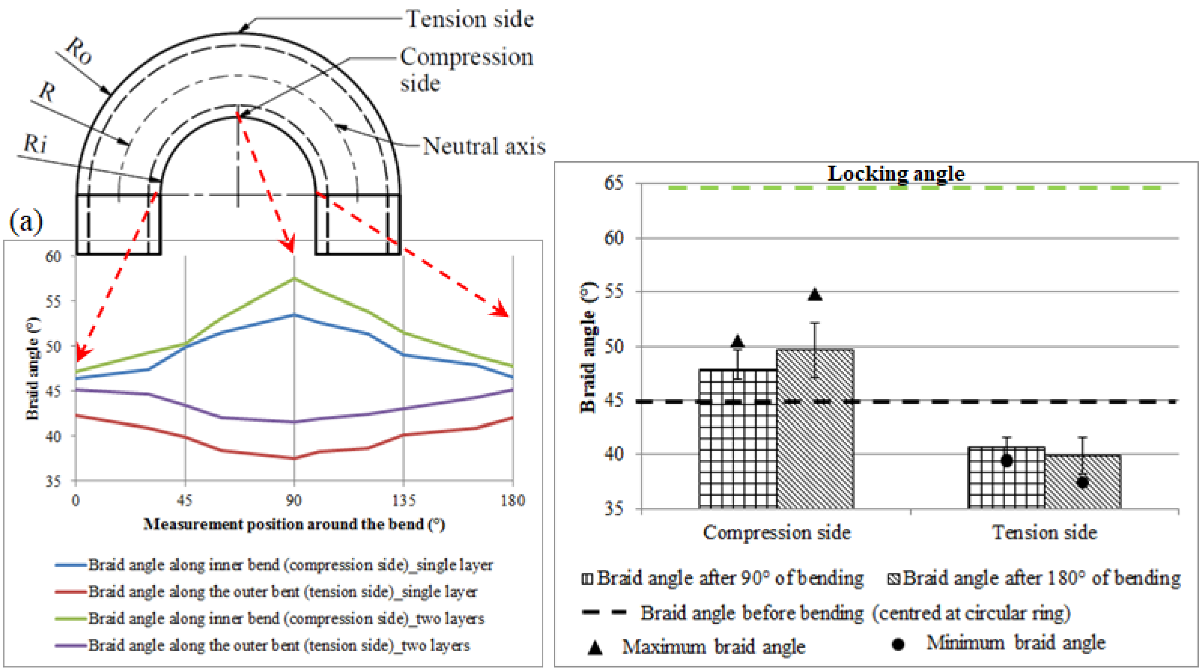
Figure 4: (a) ±45° braid on a 200-mm long braid (b) After the braid was compressed to 120 mm length and wrinkle appeared at ±65° (locking angle) (c) Braid angle changed to ±36.7° under tension (d) Graph showing predicted and measured change in braid angle (e) Predicted and measured change in braid diameter

3 EFFECTS OF BENDING ON BRAID PARAMETERS

To study the effect of bending, initially braiding was carried out to produce a ±45° braid with a mean braid thickness of 1.1 mm. 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 to 180° (U shape) using a hydraulic pipe bender (Fig. 2c).

The braid angle measurement was carried out at both tension and compression side and along the neutral axis on both sides. Along the bending curve, both on tension and compression side, a gradual change was observed from the edge of the tangent to the centre of the bending curve (Fig.5b). On the compression side, the maximum angle was observed at the centre of the bending arc and the change was significantly higher for a two-layer braid than a single layer braid. Similarly, the decrease in angle on the tension side was observed with the lowest angle located at the centre of the bending curve. Also, the reduction in braid angle under tension for two layers was lower than that of the single layer braid.
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.

Fig.5c shows the braid angle after bending for a single layer braid. At compression side, the average braid angle was higher and at tension side, it was lower than that of the neutral axis. 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. However, unlike linear compression, the diameter change is not possible due to the constraints applied during bending. Similarly, in the case of composite manufacturing, the increase in diameter is also prevented by external consolidation processes through debulking. The distortion in braid angle hence will increase the susceptibility of out of plane deformation leading to wrinkle formation during the consolidation of the composite manufacturing process.



(b) (c)

Figure 5: (a) Schematic of a 180° bent tube indicating different bending parameters (b) Graph showing the difference in the change in braid angle along the inner and outer bend of the tube with maximum change recorded at the centre of the bending arc (c) Graph showing the average braid angle for a single layer braid after bending at 90° and 180° (U shape)

4 EFFECTS OF CONSOLIDATION ON BRAIDED PREFORM

Once the bending was carried out for over-braided cores, the study observed a significant change in braid angle. However, for braided preform bending, no wrinkle appeared as the fibre tows were free to shear and relocate within the bending arc region. However, during composite manufacturing, the preform consolidation is carried out using various methods.

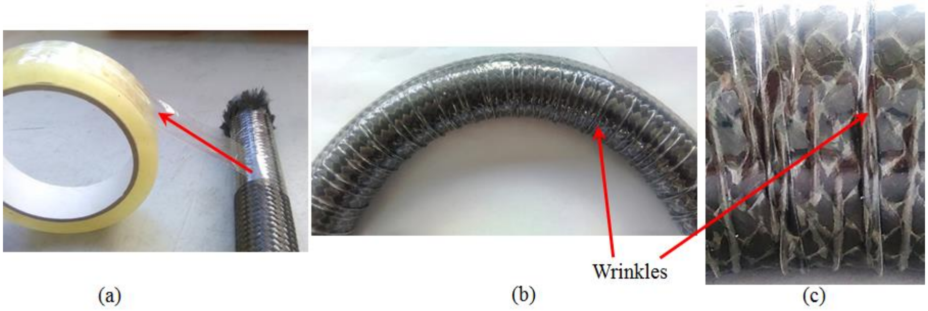


Figure 6: (a) Manual winding of adhesive tape on the braided core before bending (b) Tape over-wound single layer braid after bending with wrinkles at the inner curvature (c) Closer view of wrinkles

The example of the wrinkled tube in Fig.1a was consolidated using shrink tape wrapping. In order to replicate the consolidation method, adhesive tape was wound (Fig.6a) around the single layer braid. The pre and post consolidated braid thickness was 25.4 mm and 25.1 mm respectively. As the consolidated preform was bent to U shape, the wrinkle appeared at the inner bend with wrinkle amplitude of approximately 1 mm increasing the diameter to 26.1 mm. The appearance of the wrinkles is similar to that of the composite bent section with wrinkles (Fig.6b).

5 OPTIMISATION OF BRAID PARAMETERS

To accommodate the change of braid angle that occurs during bending, a local change in braid angle is required. By changing the rotational or linear speed of the process change in braid angle is possible to achieve however this change in angle only appears along the length of the core. The effect of bending on braid parameters showed that the change in braid angle occurs in the circumferential direction of the core. Hence, an alternative approach was taken to achieve local change in braid angle, specifically in the circumferential direction.

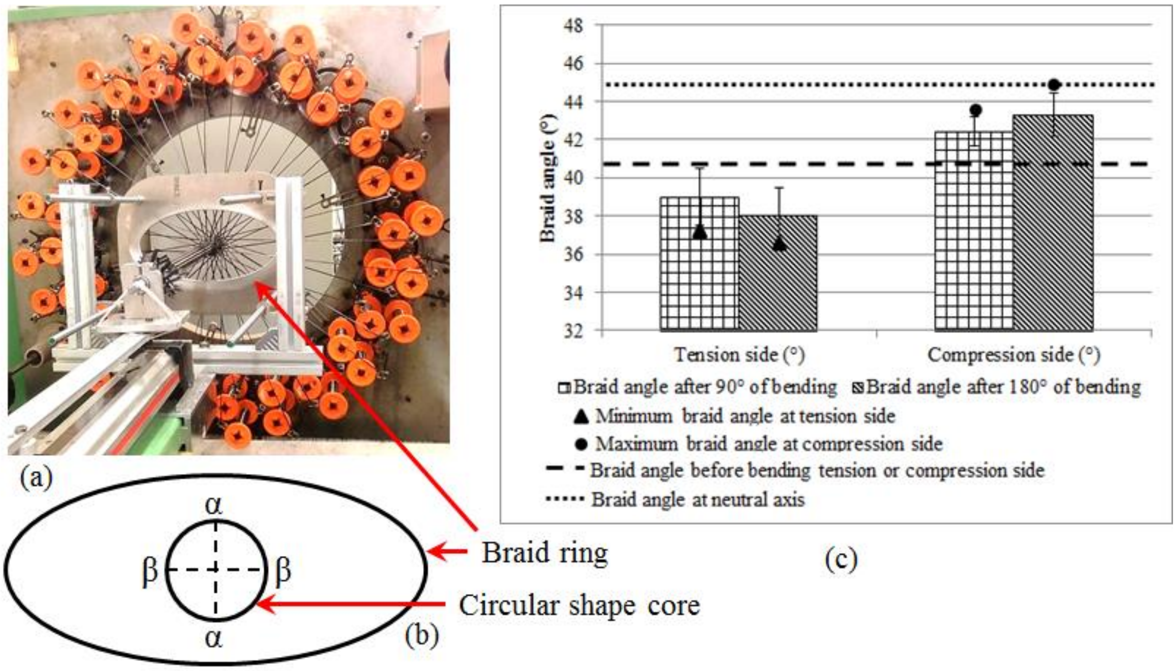


Figure 7 (a) Braiding using elliptical ring (b) Schematic diagram indicating a circular shape core at the centre of the elliptical braid ring and two braid angles at major (β) and minor dia (α) (c) Graph showing the average braid angle for a single layer braid after bending at 90° and 180° (U shape) with braid angles at major and minor diameter

Use of circular braid ring is a universally used approach for braiding process. By using an elliptical braid ring (Fig.7a) different braid angles at its major (β) and minor diameter (α) can be produced where β< α. An elliptical braid ring with 300 mm major diameter and 150 mm minor diameter was used for this study. The braid angle appears to be the same at opposing quadrants around the core (Fig.7b). During bending study a change in about ±5° was observed. Based on this observation, ±45° and ±41° braid angle was produced at adjacent quadrants of a core circumference. The over-braided core was bent to 180° while maintaining ±45° at the neutral axis. After 180° bending, it was observed that 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. Unlike the braided core with the same angle around the circumference, changing braid angle locally at compression side thus minimises the prospect of wrinkle formation.

6 CONCLUSIONS

Circumferential wrinkles were generated in composite pipes and tubes during forming of complex shapes with a high degree of bending. During bending as the section around the bending radius is subjected to tension and compression, these forces influence the braid angle to change by fibre shearing. A method for predicting the angle changes was developed considering the braid unit cell deformation similar to that of a trellis. Braid angles were measured from braided sleeves under uniaxial tension as well as compression. The measured values were in good correlation with the predicted values until the shear locking limit was reached. Beyond the shear lock limit, despite additional compressive force and deformation, no change in the angle and the braid diameter was recorded.

Over-braided cores were bent to U shape (180° of bending) to study the effect of bending on the parameters. Average braid angles were increased and decreased at the compression side (inner bend) and tension side (outer bend). Along the neutral axis, the braid angle remained constant. The change in angle was observed only in the curved region between the tangent edges. A gradual increase in angle from tangent edge to the centre of the curve was observed and the change was higher for two layers than a single layer braid. As a braid layer was consolidated by winding tape on it, after bending, circumferential wrinkle appeared around the bent section. Further study on the effect of consolidation by tape winding will be carried out for improved understanding.

Localised change in braid angle was planned to compensate for the change occurs during bending. Such change in braid angle around the circumference was achieved using an elliptical braid ring. The elliptical ring generated two different braid angles and the angles at the opposing quadrants of the braid circumference were equal. Based on the observations on the change in braid angle during bending at compression side, braiding was carried out to produce ±45° and ±40° using the elliptical ring. Bending was carried out by keeping the quadrants with ±45° braid angle along the neutral axis. Due to fibre scissoring under compression, the braid angle changed to ±45° from ±40° corresponding the angle along the neutral axis. In contrast with a braid produced using the circular ring with the same angle around the core, localised angle change improved the angle consistency around the circumference. Thus, by using the braid parameter distortion to an advantage, incidence of wrinkle formation may be minimised.

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