International Journal of Mechanics and Materials in Design manuscript No.
(will be inserted by the editor)

The effect of residual stresses and wind configuration on the allowable pressure of thick-walled GFRP pipes with closed ends

17 September 2014

Abstract An investigation into the benefits of winding thick-walled glass fibre reinforced plastic (GFRP) pipes with two layers of different winding angles is presented. It is shown that layered pipes allow significantly greater internal pressures to be carried than can be achieved by pipes wound only at ±55° if process induced residual stresses are ignored. It was found, also, that residual stresses severely reduce the allowable operating pressure of GFRP pipes. The reduction was most significant for the layered pipes, however, and this severely impacts on their utility. The most efficient pipe was nevertheless found to be a layered pipe, wound with a ±65°/±47° combination. This pipe gives a 12% improvement on the allowable pressure of the ±55° pipe. This small performance benefit is achieved at the cost of significantly greater manufacturing complexity, and so the ±55° pipe is probably still the most practical wind configuration.

Keywords Filament winding · Design · Residual Stress

1 Introduction

Composite pipes are designed to carry internal pressure and this dictates the design approach. Netting analysis [1,2] assumes that the matrix system has zero stiffness and so the fibres are required to carry all the applied loading [1]. In addition, a stress ratio of 2:1 (hoop to axial stress) is taken to exist through the wall thickness which corresponds to an internally pressurised thin-walled pipe with closed ends. The consequence of this approach is that an 'optimum' wind angle of $\pm 55°$ (more accurately 54.68°) can be calculated. When thick-walled pipes are considered, the stresses resulting from an applied internal pressure load are not constant through the thickness [3,4] which results in a stress ratio that is higher than 2:1 at the inner surface. This, together with the fact that the presence of the resin system affects the mechanical response of a GFRP pipe, brings the validity of the 'optimum' wind angle into question. In this respect, numerous investigations [5–7] have been performed in the form of pressure tests to determine whether $\pm 55°$ is actually the 'optimum' wind angle. These works indicate that this is, in fact, true for both weep and burst pressure. A number of theoretical investigations [8–11] have also been performed, where matrix properties were taken into account. These works, too, support the angle of $\pm 55°$ to within 2°, depending on the pipe geometry and material properties. The highest burst pressure is obtained for a wind angle of $\pm 55°$ since the matrix has, in most cases, developed cracks at this pressure and thus lost most of its load carrying capability. The assumption of zero matrix stiffness of the netting analysis, is therefore proved to be sound.

Pressure is, however, not the only driver of structural failure in GFRP pipes. Corrosive media can interact with the tensile stresses at the inner surface of the pipe to give rise to a common cause of composite pipe failure known as environmentally assisted cracking (EAC). EAC is highly dependant on the level of tensile stress, or strain, applied to the composite [12–16]. Increased tensile strain at the inner surface of the pipe promotes rapid growth of cracks which act as conduits that allow the aggresive media within the pipe to reach the structural fibres of the composite, which degrade under chemical attack [12, 13, 17, 18]. A corrosion resistant barrier is often employed in composite pipes and other structures that are to be exposed to corrosive environments in service. Generally the corrosion barrier [19–23] is made of a randomly oriented mat, or veil, which has a very high mass fraction (±90%) of resin, backed by layers of chopped strand mat of about 70% resin mass fraction. The high resin content of the barrier layer somewhat protects the structural filament-wound fibres behind the barrier layer by slowing the attack of the aggressive environment on the reinforcing fibres. Thermoplastic barriers are used for considerably aggressive environments [21–23]. The corrosion resistant barrier, though, does not eliminate the susceptability of the composite pipe to EAC. This has resulted in the implementation of a strain-limited [20] design approach, as specified in the design standards [21, 22, 24] for GFRP pipes. Limiting the strain has led to pipes with generally thick walls.

In thick-walled pipes with closed ends, the strain response to applied pressure is that of constant axial strain throughout the wall thickness, with circumferential strain decreasing with increased radial position [25]. This behaviour, together with the susceptability of the inner surface to EAC makes it the critical region for design analysis. Since the stress ratio is greater than 2:1 for thick-walled pipes, the circumferential principal strains at the inner surface are greater than the axial principal strains for pipes wound at ±55°. Aligning the structural fibres more in the circumferential direction increases the stiffness in this direction and hence lowers the circumferential strains. This reduces the difference in the principal strains at the inner surface of the pipe. Increasing the wind angle beyond ±55°, however, increases the stresses transverse to the fibre direction and makes the matrix more susceptible to cracking. This therefore, reduces the weep pressure that the pipe can withstand [5]. A plausible solution for this problem is to produce a pipe of two layers, each wound at different wind angles. The inner layer of the pipe is wound more circumferentially than ±55° to reduce the principal strains at the inner wall surface, whereas the outer layer is wound less circumferentially than ±55° to increase the axial stiffness and hence delay matrix cracking and weeping in the inner layer.

The discussion, so far, has neglected any mention of residual stresses. Unfortunately these are promoted by increased laminate thickness [26], to the extent that they are often comparable to the stresses arising from applied loads. The strain through the pipe thickness is the combination of both mechanical strain and residual strain. In the case of filament-wound pipes, the residual stresses that develop are generally tensile at the inner surface [26], and thus adversely affect the allowable operating pressures of pipes used to transport aggressive media. The residual stresses in composite pipes are a consequence of a number of factors including the manufacturing parameters, the resin cure shrinkage, thermal shrinkage due to elevated processing temperatures and wind angle. As a consequence, the residual stresses that develop through the thickness of pipes wound only at ±55° are different to those that develop in layered pipes wound with different wind angles. The residual strains that develop at the inner surface of each pipe configuration will therefore affect its allowable operating pressure to a different extent.

The purpose of this study is to investigate the concept of layered pipe design, and determine its effectiveness compared to the 'optimal' pipe, wound at ±55°, in terms of the strain-limited criteria set out by the GFRP pipe design standards [21, 22] for the closed-end condition. This part of the study is done using analytical techniques [25]. The validity of these results when process induced residual stresses are considered is then investigated. The residual strains in the layered pipes and the 'optimal' pipe are experimentally measured and their effect on the allowable pressures of the pipes is quantified. This allows the merit of the layered pipe concept to be determined.

2 Filament-wound pipe design

The weep pressure of GFRP pipes is directly associated with the formation of cracks within the matrix system. These cracks develop due to stress transverse to the fibre direction. The assumption made in netting analysis that the matrix system possesses zero stiffness lends itself to reducing the stress transverse to the fibre direction. Although netting analysis is associated with a 2:1 stress ratio and ignores the influence of the matrix system, the stress transverse to the fibre direction is still minimized at a wind angle of around ±55° in a thick-walled pipe even when matrix properties are considered. To illustrate this, the stresses in a GFRP pipe of thickness-to-inner-diameter ratio (t/d_i) of 0.1875 with internal pressure load, under the closed-end condition, were calculated for wind angles ranging from ±0° to ±90°. The hoop, axial and transverse strains at the inner surface, normalised against the hoop strain of a pipe wound at ±55°, are illustrated in Fig. 1. The exact elastic solution presented in the textbook of Herakovich [25] was utilised to obtain these results.

It is clear from Fig. 1 that the strains transverse to the fibre direction are minimised in the region where the wind angle is about ±55°. Fig. 1 also shows that the strain in the hoop direction for this angle is significantly larger than that in the axial direction. It therefore makes sense to align the fibres more in the circumferential direction than ±55°. Increasing the winding angle, however, results in an increase in transverse strain and thus greater susceptibility to cracking and lowered weep pressure. The transverse strain becomes increasingly similar to the axial strain at wind angles greater than about ±60°, and is thus lowered if the axial strain is lowered. One method that can be used to lower the axial strain is to increase

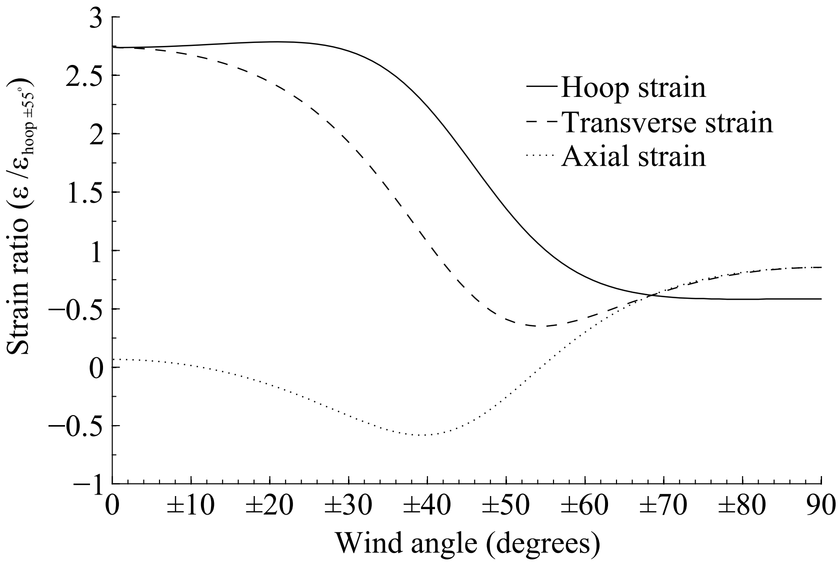

Fig. 1 Variation in strain ratio with wind angle

the overall axial stiffness of the pipe. This can be done by winding a second layer with the fibres more aligned in the axial direction. The axial strain, which is constant through the thickness [25] of the pipe, will accordingly be reduced, thereby decreasing the transverse strain of the material within the inner layer. Employing a pipe configuration which is layered should therefore allow the principal axial and hoop strains at the inner surface to be reduced, compared to a pipe wound only at ±55°, and should also lower the susceptability of the pipe to transverse cracking. This ultimately results in a more efficient design, with increased allowable internal pressures.

Up to this point, only the inner surface has been of concern, since it is the region of highest circumferential strain. Although the circumferential strain will be lower in the outer layer of the pipe, it may be high enough to cause cracking of this layer due to strain transverse to the fibre direction, since at lower fibre angles, as illustrated in Fig. 1, the transverse strain becomes increasingly similar to the circumferential strain. The circumferential, and hence transverse, strain in the outer layer will be highest at the interface of the two layers, and may need to be considered when analysing layered pipes of this nature.

2.1 Layered pipe design for this investigation

The concept of the layered pipe uses high circumferential stiffness in the inner region of the pipe to reduce the hoop strain at the inner surface, and an outer layer of high axial stiffness to limit the transverse strain in the inner layer. The gains of a layered pipe design could, however, be potentially compromised by residual stresses. For this reason, the effect of residual stresses on layered pipes needed to be investigated. In order to properly characterise the effect of residual stresses on layered pipes, and compare them to those of the $\pm 55°$ pipe, the pipes all needed to be similar. In this sense, all pipes were designed to experience a circumferential strain of 0.2%=2000$\mu\varepsilon$ for the same internal pressure. Under the closed end condition this approach is related to the strain limited design approach used to combat EAC [21, 22]. Although a corrosion resistant barrier would be employed in practice, its effect is ignored as per design specification [21, 22]. Both the maximum strain and the maximum strain transverse to the fibres need to be considered. Design standards state [21, 22] that the maximum strain within a GFRP pipe should not be greater than either $0.1\varepsilon_r$ (where ε_r is the tensile failure strain of the resin system), or a specified strain value (dependant on the resin system used), whichever is the smaller. Some design standards [24] make allowance for microcracks within the pipe and do not consider strains transverse to the structural fibre direction. This is reasonable when thermoplastic corrosion barriers are used, since the barrier is not continuous with the GRP structure and consequently prevents crack growth from the GRP towards the aggressive environment. In the case where thermoset corrosion resistant barriers are used, microcracks could easily propagate through the resin-rich barrier to the inner surface, creating a path for the aggressive media within the pipe to reach and attack the structural fibres. For this reason, the standards that deal with this situation impose various limits to avoid the formation of microcracks caused by high transverse strains. BS EN 13923 [22] specifies use of the Tsai-Hill failure criterion and a specified safety factor while BS 4994 [21] limits the allowable transverse strain to 0.1%. For the purposes of this work, the limits of BS 4994 are used. The maximum allowable strain in the pipe principal directions is taken as 0.2%=2000$\mu\varepsilon$ and the maximum allowable transverse strain is taken as 0.1%=1000$\mu\varepsilon$.

The design of the pipes made use of the elastic solution for layered composite tubes [25]. The fibre used was E-glass, and the epoxy resin system was Epikote L 1100 with the Epikure 294 curing agent. This resin system was experimentally found to have a tensile strain to failure of approximately 24000$\mu\varepsilon$. In consequence, according to BS4994, the limiting principal strain requirement of this resin system is therefore $0.1\times24000\mu\varepsilon$ which is greater than the limit of 2000$\mu\varepsilon$ specified by the standard. The strain limits specified in the previous paragraph, therefore, still conform to the requirements of BS 4994. The fibre volume fraction was specified by the manufacturer to be in the range of 0.529 to 0.567. For the purposes of this work, this was taken as 0.548, the mean value within the specified range. The material properties in the fibre coordinate system were estimated using micromechanics and are listed in Table 1. Due to the complex weave resulting from the filament winding process, no distinct sequence or stacking of plies can be identified, since these change with both circumferential and axial positions. For this reason the material properties can be considered orthotropic at the bulk scale, resulting in shear deformations uncoupled from normal stresses. Four pipes were considered, the first of these was wound at the industry standard angle of $\pm55°$. The remaining three pipes were made of two layers. All pipes had an internal diameter of 80 mm and overall wall thickness of 15 mm.

Table 1 Material properties

Longitudinal modulus, E_1 (MPa)	40887
Transverse modulus, $E_2 = E_3$ (MPa)	7905
Shear modulus, $G_{12} = G_{13}$ (MPa)	2437
Shear modulus, G_{23} (MPa)	2855
Poissons ratio, $\nu_{12} = \nu_{13}$	0.298
Poissons ratio, ν_{23}	0.384

The design condition of the $\pm 55°$ pipe with closed ends was found to occur due to the circumferential strain at the inner surface reaching the limiting strain of $2000\mu\varepsilon$. The maximum allowable internal pressure associated with this condition is 12.14 MPa. The wind angles of the inner layers of the layered pipes were specified to be higher than $\pm 55°$, for reasons already discussed. These were set to $\pm 65°$, $\pm 75°$ and $\pm 80°$, the upper limit of $\pm 80°$ corresponding with the maximum readily achievable by industrial manufacturers. The wind angle for the outer layer of each of the pipes was found such that the circumferential strain at the inner surface of each pipe was $2000\mu\varepsilon$ at the same allowable pressure as the $\pm 55°$ pipe. In this respect all pipes were equivalent. Table 2 lists the configuration of each of the resulting pipes.

Table 2 Equivalent pipes

Pipe	Inner layer	Outer layer
# 1	±55°, t=15 mm	-
# 2	±65°, t=5 mm	±47°, t=10 mm
# 3	±75°, t=5 mm	±36°, t=10 mm
# 4	±80°, t=5 mm	±29°, t=10 mm

Fig. 2 illustrates the allowable pressures of each of the pipe sections and the respective design conditions. The equivalence of all of the pipes in the design condition associated with circumferential strain at the inner surface is clearly illustrated as the constant line at 12.14 MPa (±0.03 MPa) for all wind angles. The other two lines are associated with reaching the limiting transverse strains at the inner surface, and at the inner radius of the outer layer (the transverse strain 5mm from the inner surface of the ±55° pipe is included for clarity). Limiting the axial strain within the layered pipes by aligning the fibres of the outer layer more in the axial direction results in an increased resistance to transverse cracking at the inner surface. This is a desired result, but Fig. 1 indicates that it cannot be achieved by a single layered pipe of high wind angle. Returning to Fig. 2, transverse strains in the material of the outer layer of the ±75°/±36° and ±80°/±29° pipes, however, surpass the imposed strain limit of $1000\mu\varepsilon$. This could be deemed a failure in terms of BS 4994, which states [21] that *“it shall be ensured that the strain transverse to the fibre direction is less than 0.1%”*. The susceptibility of the inner surface of the pipes to EAC, however, is small. Since the interface between the layers of each of the layered pipes is far removed from the inner surface, microcracks in this region would likely play no role in EAC. The transverse strains of the inner layer are much lower than the allowable limit of $1000\mu\varepsilon$, making it highly unlikely for the cracks to propagate through the inner layer. Under these cicumstances the allowable pressures of the ±75°/±36° and ±80°/±29° pipes remain the same as that of the ±55° pipe under the circumferential strain design condition.

3 Residual stress

The inner surface of a composite pipe under pressure, layered or not, is the region of highest strain. This is also the surface that is in contact with potentially aggressive media and is the region where EAC occurs. For this reason, only the residual strains at the inner surface of a pipe are needed to characterise the effect of residual stresses on the allowable operating

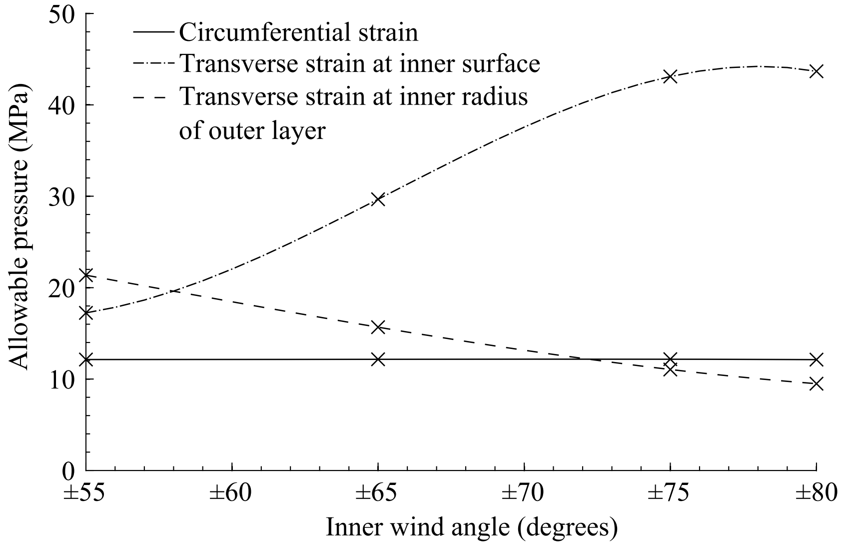

Fig. 2 Allowable pressures with respect to the critical failure strains

pressures. The residual strains at the inner surface were obtained by employing a parting procedure. The following section describes the manufacture of the test pipes, and the experimental procedure used to measure the residual strain at the inner surface of the pipes.

3.1 Manufacture

The pipes were manufactured by GRP Tubing (Pty) Ltd of Somerset West, South Africa. The first of the pipes was wound entirely at the industry standard winding angle of ±55°. The cure cycle consisted of curing the pipe at room temperature for a period of 12 hours, followed by 2 hours at 60°C and then 8 hours at 80°C. Once cured, the pipe was ground to the desired thickness of 15 mm and then removed from the steel mandrel. The three remaining pipes were each made up of two different winding angles, as specified in Table 2. The layered pipes were manufactured in two stages. The first stage consisted of winding the inner section and curing it in the same manner as with the ±55° pipe. The inner section was then ground to the desired thickness of 5 mm, after which the outer section was wound and cured. After the final cure, the pipes were ground to the desired overall thickness of 15 mm and the mandrel was removed.

3.2 Experimental Method

Test sections of 120 mm in length were cut from each pipe. Finite element analysis showed that the residual stresses in the central region of a section of this length are within 5% of those of a pipe of infinite length. Three sets of strain gauge rosettes (orientated at 0°, 45° and 90° relative to the axial direction) were bonded to the inner surface at the mid-length of each test section and located circumferentially at 120° to one another. Residual strains on the inner surface of the pipes were measured by removing the material comprising the majority of the wall thickness and then employing a parting procedure where the wall around the strain gauge rosette was cut through. This effectively released the residual stress, and the final measured strains in each rosette were assumed to be exactly equal and opposite to the residual strains that existed on the inner surface of the pipe prior to any machining process. The majority of the wall thickness was removed using a cylindrical grinding machine. Grinding forces and heat input were minimised by removing only 0.025 mm from the wall thickness during each pass of the grinding wheel. The use of a thermal imaging camera revealed that the maximum temperature that the test pieces reached during machining was in the region of 42°C, as seen in Fig. 3, well below the peak cure temperature of 80°C. Under these conditions it is reasonable to assume that the induced machining stresses are negligible.

The test sections became increasingly fragile as the wall thickness reduced. The grinding process was accordingly terminated when the wall thickness reached 0.6 mm to avoid

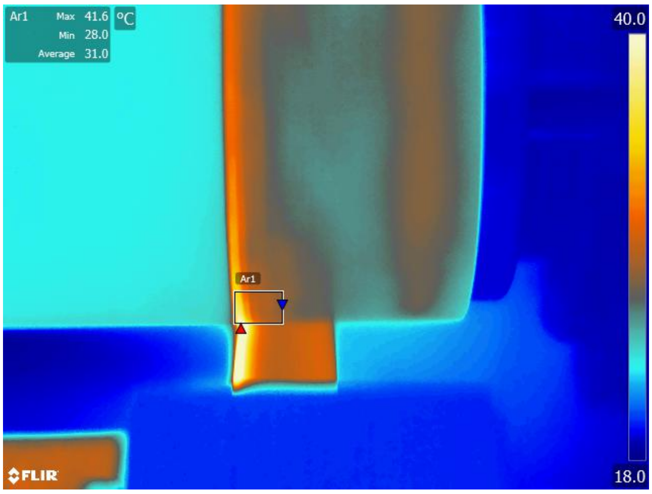

Fig. 3 Thermal image during grinding

damage to the test sections. A diamond coated disc was used to cut around each strain gauge rosette once the grinding process was completed. This process was also done using small increments in depth to prevent heat and consequent stress build up. Strain measurements were recorded using a National Instruments data acquisition system equipped with SCXI-1520 and SCXI-1521/B strain cards. The measured strain data were referenced to a single temperature to ensure that the measured strain change was solely due to mechanical effects.

3.3 Results and discussion

Residual strain measurements of the ±80°/±29° pipe could not be obtained since this pipe cracked on the inner surface during manufacture. The cracks were orientated parallel to the ±80° fibre direction, which indicates significant residual strain transverse to the fibre direction. The measured residual strains at the inner surface of each of the remaining test sections are presented in Table 3. It is evident that the residual strains in the circumferential direction, ε_θ, have been significantly reduced by employing a two stage manufacturing process with different wind angles. The ±65°/±47° pipe shows an average reduction in circumferential residual strain of 15% when compared to the ±55° pipe. The axial residual strain, ε_x, however, increases by 80% but is still lower than the circumferential residual strain. The ±75°/±36° pipe has a circumferential residual strain reduction of 43%. The axial residual strain increase is, however, 126% as compared to the ±55° pipe. In this case, the axial residual strain now becomes critical and so the maximum residual strain of $963\mu\varepsilon$ is only reduced by 16% when compared to the $1153\mu\varepsilon$ of the ±55° pipe. The increased axial residual strain in the layered pipes indicates an increase in the residual strain transverse to the fibre direction, ε_t, in the inner layer. The increase in transverse strain with wind angle is clear from the data presented in Table 3 and is the reason for the failure of the ±80°/±29° pipe during manufacture.

The strains at the inner surface of the pipes comprise the combination of both the mechanical strains, due to the internal pressure and the residual strains arising from the manufacturing process. Since the allowable tensile strains at the inner surface of the pipes are limited by the design codes, and since the residual strains presented in Table 3 are all tensile, the allowable pressures that can be applied to the pipes are all reduced. The effect of the measured residual strains on the performance on the pipes is presented in Fig. 4. The analysis is based on the combination of analytically determined strains arising from internal pressure and the experimentally measured residual strains. Allowable pressure is determined by considering the design limitations on both circumferential and transverse strains at the inner surface. Error bars are based on a standard deviation of $40\mu\varepsilon$ which is the average measured for all residual strain readings. For comparison purposes, Fig. 4 also shows the allowable pressure associated with the circumferential direction when residual strains are not taken into account. This was the condition that was used when designing the pipes to be equivalent. When residual strains are considered, it is apparent that the allowable operating

Table 3 Inner surface residual strain

Pipe		Strain gauge measurements			Calculated
		ε_x ($\mu\varepsilon$)	ε_θ ($\mu\varepsilon$)	ε_{45} ($\mu\varepsilon$)	ε_t ($\mu\varepsilon$)
±55°		417	1195	794	673
		458	1122	764	676
		405	1142	840	648
	Average(A)	427	1153	799	666
±65°/±47°		896	944	857	905
		754	1008	804	799
		660	998	861	720
	Average(B)	770	983	841	808
	B/A	1.80	0.85	1.05	1.21
±75°/±36°		899	715	808	887
		1010	636	845	985
		982	628	892	958
	Average(C)	963	660	848	943
	C/A	2.26	0.57	1.06	1.42

pressure of all pipes is considerably reduced. It is also clear that as the winding angle of the inner layer increases, the allowable load becomes more sensitive to the residual strain in the direction transverse to the fibres. This reflects the fact that the transverse residual strain increasingly approaches the strain limit of $1000\mu\varepsilon$ as the wind angle increases. Residual strains cause the maximum allowable pressure of the ±55° pipe to be reduced by 58% in comparison to the pressure when the residual strains are ignored. Similarly, the allowable pressures of the ±65°/±47° and ±75°/±36° pipes are reduced by 53% and 80%, respectively, when residual strains are considered. It is clear that residual strains play a significant role in the overall performance of thick-walled GFRP pipes and should, in some way, be considered in the design procedure.

It is interesting to note that the limiting factors in the design of the layered pipes differ from those of the ±55° pipe when residual strains are considered. The limiting factor of the ±55° pipe is unaffected by the residual strains and remains the principal circumferential strain reaching $2000\mu\varepsilon$, whereas that of the layered pipes changes to the strain transverse to the fibre direction reaching the limit of $1000\mu\varepsilon$. This is unfortunate because the use of layering is intended to maximize the performance of these pipes under the circumferential strain design condition. The change in the limiting factor to the strain in the transverse direction is interesting because Fig. 2 shows that the response of the layered pipes to internal pressure results in lower susceptibility to cracking at the inner surface as the inner layer wind angle increases. The severity of the transverse residual strains increases with increased wind angle, however, and thus negates the desired mechanical response of the layered pipes. In the extreme case, the ±80°/±29° pipe, the transverse residual stresses caused failure of the pipe during manufacture.

Fig. 4 indicates that the ±65°/±47° pipe is the best of the four pipes considered. It has the highest allowable pressure load of 5.7 MPa. This is, however, only a 12% increase on the allowable pressure of the ±55° pipe. Whether or not the more time consuming and complex manufacturing procedure of the layered pipes is justifiable for such a small increase in performance is, however, debatable. This investigation is limited and has not exhausted the full combination of all variables. The results, however, provide a meaningful contribution to understanding the effect of residual stresses in layered pipes.

4 Conclusions

The concept of pipes made up of two layers, wound at different wind angles, has been investigated. If the presence of residual stresses is ignored, it appears that layered pipes could

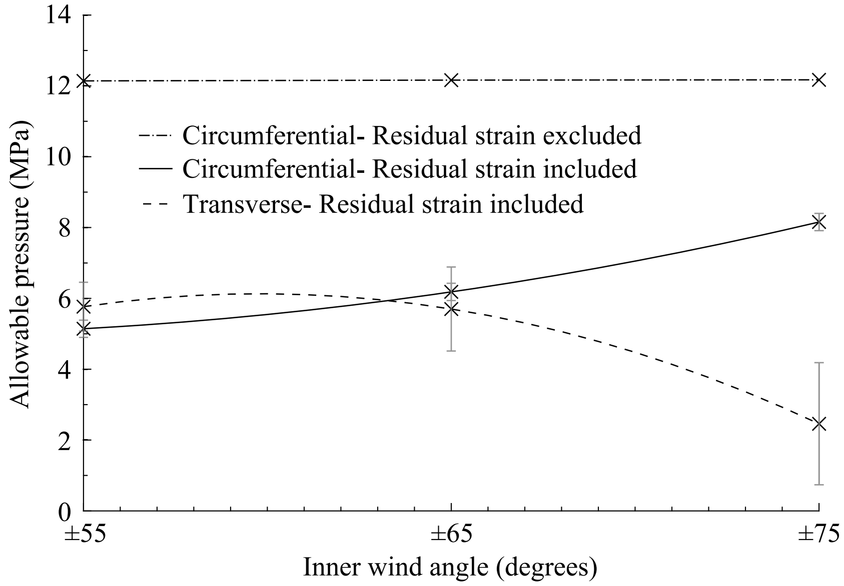

Fig. 4 Allowable pressure associated with principal and transverse strains

support higher internal pressure than the typical pipe wound only at ±55°. When residual strains are considered, however, it is apparent that the allowable pressures of the layered pipes and the pipe wound only at ±55° are considerably reduced. The presence of residual strains changes the limiting factor in the design of the layered pipes from circumferential strain to transverse strain, thereby negating many of the advantages of layering. Although a pipe wound at ±65° in the inner layer and ±47° in the outer layer still has 12% better performance than the ±55° pipe when residual strains are considered, its increased manufacturing complexity may not be justifiable.

Acknowledgements

The support of the DST-NRF Centre of Excellence in Strong Materials (CoE-SM) towards this research is hereby acknowledged. Opinions expressed, and conclusions arrived at, are those of the authors and are not necessarily to be attributed to the CoE-SM.

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