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Tailored local design of deep sea FRP composite risers

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The use of fibre reinforced polymer (FRP) composite materials in offshore engineering for deep sea riser systems has drawn considerable interest due to the potential weight savings and improvement in durability that can be achieved. The design of FRP composite risers consists of two stages: (1) preliminary local design based on critical local load cases (LCs) and (2) global analysis of the full length composite riser under global loads including platform motion, hydrostatic pressure, gravity, buoyancy, wave and current loads to determine and assess critical locations. The preliminary local design stage is necessary to obtain a first estimate of the laminate configuration – fibre orientations and layer thicknesses of the tube wall, since the deformations and hence the forces and bending moments due to the global loads, depend on the geometric configuration. This paper describes the methodology, LCs, analysis procedure and results of the first stage, the local design of the composite riser. The local design is conducted using five different LCs as prescribed by the standards. In this study, geometric configurations of eight different composite body and liner combinations were optimised to provide minimum structural weight. Previous composite riser designs have mainly focused on axial and hoop reinforcements; in the present study, fibre reinforcements at other orientations are included. The highlight of the current study is that it shows that the use of off angle fibre orientations in addition to axial and hoop reinforcements offer substantial weight savings.

Keywords: offshore engineering; composite riser; FRP composite material design; finite element modelling; local design

1. Introduction

Risers are indispensable components of the exploration and production systems and their structural integrity is critical to safe field operations. Based on their function, risers are classified as *drilling risers,* which are used to guide the drill stem and conduct the drilling fluid upwards, and *production risers* which raise the extracted oil or natural gas to the floating platform.[1,2] In terms of their design, there are *rigid Top Tension Risers* (TTR), *standard Flexible Risers* and *alternative Flexible Risers*.[1–3] Drilling risers are mostly rigid and almost always top tension. Flexible production risers installed in several ways including the free hanging, lazy S, steep S, steep wave, tethered S and Chinese lantern configurations. However, rigid production risers are mostly installed in the TTR configuration.[4–6] This study employs the TTR as the model to illustrate how greater weight savings can be achieved using tailored composite design with fibre reinforcement angles optimised for maximum structural

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efficiency. The approach can easily be extended to other types of composite risers and pipes to achieve weight savings through tailored design. A typical offshore production platform may have up to 40 risers, with each riser consisting of as many as 100 large diameter tubular segments making up its length. To eliminate compressive stresses and maintain the riser's position, a top tension is normally applied to the risers. Currently, offshore oil and gas industry uses production risers made of high grade steel. The weight of such large steel structure has limited the capacity of offshore operations to move into deeper waters. Consequently, the top tension required to keep it in the desired position increases with increasing depth of the subsea wellhead. At the same time, the top tensioning capacity of the offshore platform limits the number of risers that can be attached to it. Hence, if the weight of individual riser can be reduced, it would become possible to exploit the greater amount of oil and gas resources available in deeper waters and to increase the production capacity of existing platforms, resulting in significant financial benefits.

Due to the desirable mechanical properties and low density of advanced fibre-reinforced polymer (FRP) composites, it has been widely recognised that their use for the manufacturing of deep sea oil production riser systems would lead to considerable weight savings. These savings will reduce the operation cost of existing platforms due to low tension requirement for lighter riser and will also facilitate extraction of oil and gas from greater depths.[7–9] In comparison to steel, FRP composites also have better thermal insulation properties, corrosion and fatigue resistance, which provide additional benefits by reducing maintenance cost. Another advantage of using FRP composites is that the design can be tailored for specific requirements providing a wider range of configuration possibilities with different matrix and fibre reinforcement combinations, variations in fibre orientations, different stacking sequences and different liner materials.

Generally speaking, filament winding is well suited to automation where high tension results in higher rigidity and strength; lower tension results in more flexibility; the fibre angle determines the properties of the final product. It is desirable to reduce production costs and time to increase the competitiveness of composite material products. A typical example is the case of FRP pressure vessels for which advanced manufacturing technologies [10,11] have been developed, (e.g. mass production of polymer liners and high speed 'dry winding' of filaments [10]), and parametric studies have been conducted [12–15] to develop optimal winding patterns and structural designs. However, such studies of composite risers have still to be developed.

In the past three decades, there have been several attempts to design and fabricate riser segments out of FRP composites. In the 1980s, the Institut Francais du Petrole and Aerospatiale of France undertook a project to evaluate composite offshore tubular structure.[16] Their design consisted of orthogonal reinforcements with glass fibre-reinforced circumferential layers and carbon fibre-reinforced longitudinal layers and a Buna inner liner. Static burst and tension tests, fatigue and creep tests were conducted and proved that this composite riser tube was capable of carrying the expected mechanical loads. In the mid nineties, the National Institute of Standards and Technology (NIST) Advanced Technology Programs (ATP) developed and tested composite riser tubulars for applications at water depths between 1000 and 1500 m.[17] The tube body was a hybrid composite structure, consisting of carbon and E-glass fibres in an epoxy matrix. The low angle off axis and circumferential carbon fibre reinforcements provided axial and circumferential strength and stiffness, respectively. After a series static and cyclic fatigue tests, it was found that these composite riser tubes met both performance and cost requirements. In the joint industry project led by Norske Conoco AS and Kvaerner

Oilfield Products (KOP), a demonstration composite drilling riser joint (a tube segment) was installed in field on Heidrun Tension Leg Platform in July 2001.[18] The drilling riser joints had hydrogenated nitrile rubber and titanium as internal liner materials; titanium was also used for the connectors. The field testing clearly proved that composite riser joints can meet rigorous offshore requirements. ConocoPhillips, KOP and ChevronTexaco jointly funded a composite riser project (Magnolia Project) in March 2003.[19] The purpose was to replace a few steel joints with composite joints on the Magnolia Tension Leg Platform, which operated at a depth of about 1425 m. The projected structural weight saving over steel for a 19.2 m joint was around 48%. Unlike the NIST and ATP projects, the Magnolia project used steel for the liner and the connectors to make the composite riser joints more economical. However, the composite riser joints could not be installed on the Magnolia platform because there was a leak in the liner at the final stage field test, throwing doubt on the steel liner's pressure integrity.[20] More recently, Doris Engineering, Freyssinet, Total and Soficar entered into a joint venture to develop carbon fibre-reinforced thermoplastic (PA11) tubes for 2000–3000 m water depths.[21] In this project, ±55° reinforced angle layers were included for the first time to increase burst resistance. The burst, tension and collapse calculations and tests showed that the thermoplastic composite riser is technically feasible and more qualification tests are being conducted. In July 2009, Airborne Composite Tubulars, MCS Advanced Sub-sea Engineering and OTM Consulting organised a joint industry programme [22] to prove the concept of a thermoplastic composite riser, but no further details about this are currently available in the open literature. While most previous designs of composite risers employed the simple approach of having fibre reinforcements in the hoop and axial directions separately, the cooperative venture by Doris Engineering and others [21] introduced fibre reinforcements at ±55° angle in an attempt to improve efficiency and achieve further weight reduction on the basis of netting theory.

According to netting theory, ±54.7° is the most efficient reinforcement angle for a filament wound thin cylindrical pipe under internal pressure with end effect (burst case for riser design), which has a hoop stress to axial stress ratio of 2:1. With fibres laid at this optimum angle, reinforcements are not required in any other direction.[23,24] While the same minimum weight can be achieved with reinforcements in multiple directions also by appropriately choosing their thickness ratios, having a single fibre orientation also reduced the manufacturing effort.[24] Netting theory assumes that all the loads are carried by the fibres located in each layer and no stresses are developed in the transverse direction. However, if the stiffness in the transverse direction is taken into account, stresses will develop in the transverse direction to the fibres and can cause matrix failure. Further, the optimum angle is calculated using thin shell assumptions and is therefore not valid for thick tubes. Hence, for a thick laminated composite pipe, ±54.7° does not represent the most efficient direction for fibre reinforcement under internal pressure with end effect. The minimum laminate thickness also depends on the ratios of the transverse (and shear) stiffness and strength to those in the fibre direction. For a production riser with top tension, the ratio of the hoop stress to axial stress is not 2:1. Hence even for thin tubes, ±54.7° is no longer the angle of optimum reinforcement orientation.[25] For these reasons, we need to separately evaluate optimum reinforcement directions for thick laminated tubes under specific load cases (LCs) to achieve the maximum weight reduction.

The earlier composite designs and their prototype tests have clearly shown that FRP composites can indeed provide a substantial weight saving over steel.[7–9] Optimising the fibre orientations to take full advantage of their reinforcement strengths can reduce weight further providing more economic benefits. In the local design reported in this paper, the effects of fibre orientations and stacking sequences on the weight of the composite riser are investigated using composite laminate theory that takes into account the transverse and shear properties of the composite material. The structural weight of a typical riser joint obtained with the optimised fibre orientations and the stacking sequence is compared to weight of the composite riser using conventional design (reinforcements in hoop and axial directions only) and that of the steel riser. The design study is conducted using the five main LCs recommended for local design of subsea riser systems by the American Bureau of Shipping.[26]

Section 2 demonstrates how application of classical laminate plate theory taking into account the transverse and shear properties of the laminae yields optimum fibre orientations and minimum thicknesses that are significantly different from those predicted by netting theory using examples of 4 and 8 ply laminate tubes under burst case. The material properties, finite element model, design methodology and LCs employed in the local design of composite tubulars for minimum weight are described in Section 3. The results of two typical material combinations are presented in Sections 4 and 5. The design result with matrix cracking permitted (AS4/PEEK with PEEK liner) is compared to that of without matrix cracking in Section 6. Section 7 presents the results for all material combinations studied.

2. Minimum thickness for pipe under internal pressure using classical laminate theory

For the local design process of composite riser tubulars, the burst LC is the predominant one among the five LCs. Normally, the axial force due to the end effect of internal pressure in the burst case is much higher than that caused by the consideration of top-tension case alone. Therefore, the burst LC, i.e. the case of a cylindrical tubular with closed ends under internal pressure, is employed here to study the effect of varying fibre reinforcement angle on the minimum laminate thickness. As noted in the introduction, the optimum angle for reinforcement of a filament wound thin cylindrical pipe under internal pressure with end effect is given by netting theory as ±54.7° and the corresponding minimum thickness as $1.5pr/\sigma_1$, where p is the internal pressure, r the mean radius and σ_1 the ply strength in longitudinal direction.[24] However, for a composite with fibres embedded in a matrix, transverse and shear stresses come into existence due to the matrix stiffness and failure of the matrix due to these stresses also have to be considered.

2.1. Minimum thickness for four plies balanced symmetric laminates

In this section, classical laminate theory [27] is used to determine the minimum thickness required for a pipe under the burst load (internal pressure with end effect), as a function of fibre reinforcement angle for different values of transverse stiffnesses and strengths in comparison to those in the fibre direction. Initially, a four plies laminate is considered, with a lay-up of $(\pm\theta)_{\text{symmetric}}$. For this lay-up, all four plies have the same thickness, since the magnitudes of the stresses are the same in all the plies. First ply failure using the maximum stress failure criterion [27] is applied (to normal stresses in the fibre and transverse directions and the in-plane shear stress) to determine the minimum ply thickness required and hence the minimum laminate thickness.

Figure 1 shows the variation of minimum laminate thickness, normalised with respect to the value given by netting theory ($1.5pr/\sigma_1$), for the four plies $(\pm\theta)_{\text{symmetric}}$ laminate required to satisfy the strength criteria as function of fibre reinforcement angles θ. Noting that the normalised ply thickness required is a function of the ratios of the transverse stiffnesses and strengths to those in the fibre direction, namely E_2/E_1 and S_2/S_1. Figure 1(a) and (b) respectively shows the variations of the minimum laminate thickness with the reinforcement angle for different values E_2/E_1 and S_2/S_1, with the other strength and stiffness ratios held constant in each case. The minimum values of the stiffness and strength ratios used in these plots, i.e. $E_2/E_1 = 0.07$, $G_{12}/E_1 = 0.04$, $S_2/S_1 = 0.03$ and $S_{12}/S_1 = 0.04$, are those corresponding to carbon fibre AS4 reinforced epoxy with a fibre volume fraction of 0.6, the mechanical properties of which are listed in Table 1.

The reason for the sharp changes in the gradients of some of the curves in Figure 1 is the shift in failure mode from that caused by transverse stress to that caused by shear. For example, for all the curves in Figure 1(a) except that of $E_2/E_1 = 0.07$, the failure occurs under transverse stress. All these curves are smooth. In the case of $E_2/E_1 = 0.07$, the cause of failure shifts from transverse stress to shear stress at an angle of about 39° and back to transverse stress at about 51°, producing the sharp changes in the gradients of the curve at these locations. The variation of the tube thickness with fibre orientation given by netting theory is also plotted in Figure 1(a) for comparison. The minimum in this curve occurs at $\theta = \pm 54.7°$ and has a normalised value of 1.0. For all the properties considered in Figure 1(a), the minimum thicknesses predicted by laminate theory are higher than that given by netting theory, increasing with increasing values of the transverse stiffness ratio E_2/E_1. Figure 1(b) shows that the minimum required thickness decreases with increasing values of the transverse strength ratio S_2/S_1 and drops below that given by netting theory for values of S_2/S_1 equal to and greater than 0.07. It is also seen that the region dominated by shear failure (the central portion of the curves defined by the sharp gradient changes) becomes larger as the transverse strength ratio increases.

The optimum angle of reinforcement for minimum thickness of the four plies lay-up with the stiffness and strength ratios corresponding to those of AS4/epoxy is

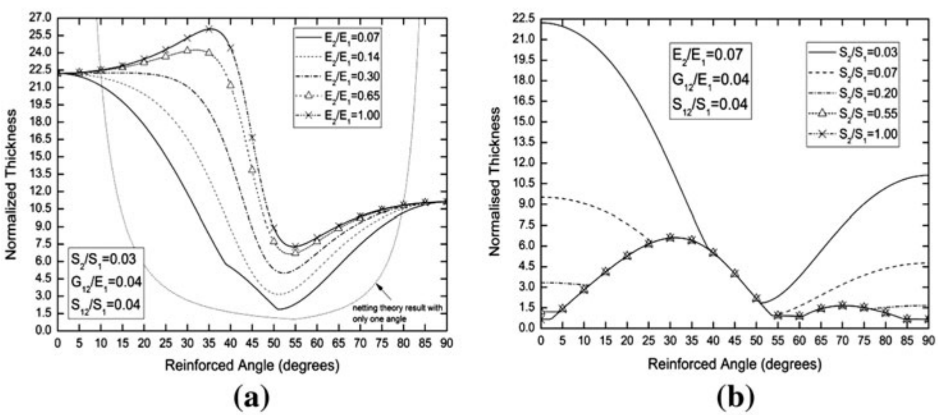

Figure 1. Variation of normalised thickness of four plies ($\pm\theta$ symmetric) laminate with fibre reinforcement angle for (a) different values of E_2/E_1 and (b) different values of S_2/S_1.

Table 1. Long-term mechanical properties of unidirectional FRP reinforced lamina considered in the design.

Name	Fibre volume fraction	Density [kg/m^3]	E_1 [GPa]	$E_2 = E_3$ [GPa]	$G_{12} = G_{13}$ [GPa]	G_{23} [GPa]	$\upsilon_{12} = \upsilon_{13}$	υ_{23}	σ_1^T [MPa]	σ_1^C [MPa]	σ_2^T [MPa]	σ_2^C [MPa]	τ_{12} [MPa]
AS4-Epoxy	0.60	1530	135.4	9.37	4.96	3.20	0.32	0.46	1732	1256	49.4	167.2	71.2
AS4-PEEK	0.58	1561	131.0	8.70	5.00	2.78	0.28	0.48	1648	864	62.4	156.8	125.6
P75-Epoxy	0.60	1776	310.0	6.60	4.10	2.12	0.29	0.70	720	328	22.4	55.2	176.0
P75-PEEK	0.55	1773	280.0	6.70	3.43	1.87	0.30	0.69	668	364	24.8	136.0	68.0

obtained as 51° using classical laminate theory with the minimum thickness being 1.84 times that given by netting theory. It is also seen show that if the transverse stiffness to longitudinal stiffness (E_2/E_1) is increased, the optimum angles increases from 51° and the minimum thickness required rises significantly. On the other hand, if the transverse strength ratio (S_2/S_1) is increased, the optimum angle increases and the minimum thickness required reduces to values well below that predicted by netting theory. This is significant as it indicates that by embedding the AS4 fibres in a stronger matrix, we can reduce the thickness of the tubular required to withstand the burst pressure.

2.2. Minimum thickness for eight plies balanced symmetric laminates

The analysis performed on the four plies laminates was extended to four plies balanced symmetric laminates with orthogonal reinforcements, i.e. with $[\pm\theta, \pm(90-\theta)]_{\text{symmetric}}$ lay-up, to determine the minimum thickness under internal pressure with end effects. It may be noted that since the stresses are in-plane, the stacking sequence has no effect. However, the thickness of the θ layers and the $(90-\theta)$ layers is, in general, different. The total laminate thickness is thus the sum of the thickness of the θ layers and thickness of the $(90-\theta)$ layers. As before, the maximum stresses in the fibre direction, transverse direction and shear are compared to their strength values to determine the minimum thickness of each ply required.

Figure 2(a) and (b) respectively shows the variations of the minimum laminate thickness with the reinforcement angle for the eight plies laminate with $[\pm\theta, \pm(90-\theta)]_{\text{symmetric}}$ lay-up for different values E_2/E_1 and S_2/S_1, with the other strength and stiffness ratios held constant in each case.

The trends seen in these figures are similar to those seen for the four plies laminate, with the minimum required laminate thickness increasing with increasing values of the stiffness ratios E_2/E_1 (Figure 2(a)) and decreasing with increasing values of the transverse strength ratio S_2/S_1 (Figure 2(b)). However, surprisingly, it was found that the optimum angle of reinforcement and the minimum laminate thickness for the eight plies laminates were exactly the same as those obtained for the four plies laminates for all the stiffness and strength combinations investigated. The reason for this is that when one of the plies has an orientation in the mid-range, the thickness of the layers

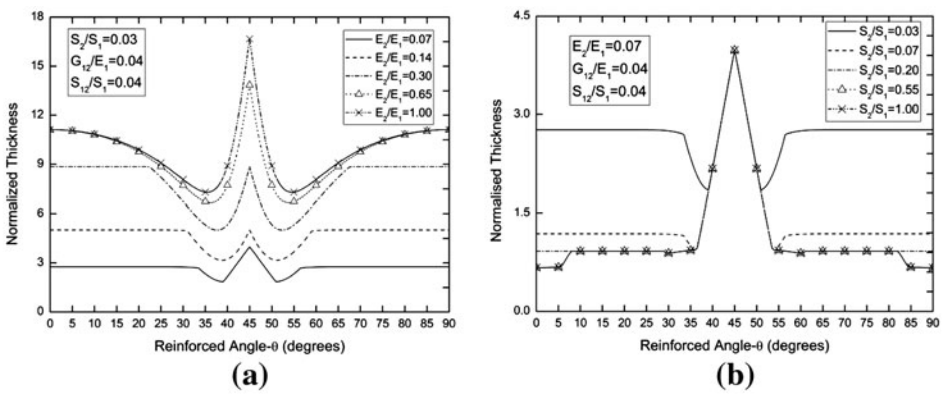

Figure 2. Variation of normalised thickness of eight plies ($\pm\theta$, $\pm(90-\theta)$ symmetric) laminate with fibre reinforcement angle for (a) different values of E_2/E_1 and (b) different values of S_2/S_1.

perpendicular to it turns out to be zero for the required laminate thickness. When half the layers are oriented with values of $\pm\theta$ in the mid-range, the transverse strain in these plies becomes relatively small, causing low transverse stresses. The thickness of these plies is then adjusted to prevent failure in the fibre direction, and they become sufficient to carry all the loads without requiring any plies in the orthogonal direction. For values of θ away from this region, the total laminate thickness for the eight laminate is much lower than the total thickness for the four plies laminate. This is because the when the fibres are oriented close to the axial or hoop direction of the pipe in the four plies laminate, their thickness has to be increased significantly to accommodate the transverse stresses; whereas in the eight plies laminate with orthogonal fibre reinforcement, both the hoop and axial stresses are mainly resisted by the fibres.

From the results of the analysis using classical laminate theory presented here, it is clear that the optimum angle of reinforcement for thin-walled composite pressure vessels (constructed with fibres embedded in a matrix) is not 54.7° and the smallest thickness is not $1.5pr/\sigma_1$. The optimum angle and the minimum thickness both depend on the stiffness and strength ratios. For composite with high matrix strength, the minimum required wall thickness is significantly lower than that predicted by netting theory. It is to be noted that the above analysis and the netting theory are strictly valid only for thin-walled pressure vessels. Analysis using 3D laminate theory will be necessary for thick laminates; however, it is clear that the minimum thickness required for thick tubes will also depend on the stiffness and the strength ratios.

3. Local design of composite tubulars for minimum weight

The foregoing 2D analysis clearly shows that even for thin laminates, the optimum angle of reinforcement and the minimum thickness required for a tube with internal pressure are different from those predicted by netting theory, due to the finite stiffness and strength of the matrix. It may be noted that the result from theory would be valid only for one ratio of the circumferential stress resultant to the axial stress resultant (provided it is thin walled); if this ratio changes from that for which the reinforcement angle is chosen, the fibres will no longer be able to bear the load. For instance, if the reinforcement angle is chosen as 54.7°, to minimise the tube thickness only for internal pressure, any additional tension, such as that due to top tension in the riser, will have to be borne by the liner. Further, netting theory is based on thin-wall assumptions, which no longer hold good for thick tubes, in which the variation the circumferential lengths of the layers causes a further variation in stress distribution across the laminae. For accurate estimation of stresses in thick-walled tubes, it is necessary to do a 3D analysis, which is performed here using 3D solid elements in ANSYS. The sections below describe the modelling approach and the methodology employed for local design of the composite riser tubular for minimum weight. The analysis is conducted for the 'conventional' orthogonal design (axial and hoop reinforcements) employed so far, as well as for the 'tailored' design using fibre reinforcements in other orientations in additional to the axial and hoop directions.

3.1. Material selection and properties

As the 2D analysis in Section 2 shows that the optimum reinforcement angle and the minimum thickness depend on the matrix to fibre strength and stiffness ratios, the combination of constituent materials (fibre, matrix and liner) is considered as a design parameter that can influence the structural weight. In general, carbon fibre-reinforced composites have higher specific stiffness and strength, better fatigue characteristics, lower thermal expansion coefficients, higher stress corrosion resistance and greater durability in seawater.[8,27] In this study, both high strength carbon fibre AS4 and high modulus carbon fibre P75 are investigated since it was not apparent at the beginning as to which of these properties would dominate in providing higher weight savings. Two types of matrices are considered for the structural composites, epoxy (thermoset) and PEEK (thermoplastic). Epoxy has good mechanical properties and water resistance and is well suited for filament winding.[27,28] PEEK has a high damage tolerance and low water absorption [29] and is the most popular thermoplastic used for offshore composite tubulars. When thermoplastic is employed as matrix for the structural body, it is common to use the same thermoplastic for the liner also in order to avoid debonding [21]; the same approach is used in this study.

The unidirectional lamina properties for the four different fibre and matrix combinations, AS4/epoxy, AS4/PEEK, P75/epoxy, P75/PEEK, employed in the FEA, are listed in Table 1. The material properties in 3D consist of the elastic moduli (E_1, E_2, E_3), shear moduli (G_{12}, G_{13}, G_{23}), Poisson's ratios (υ_{12}, υ_{13}, υ_{23}) and the in-plane strengths (σ_1, σ_2, τ_{12}), where the subscripts 1, 2 and 12 stand for the fibre direction, transverse direction and in-plane shear, respectively. The Young's moduli of the P75/epoxy and P75/PEEK laminae in the fibre direction are more than twice those of the composites with AS4 reinforcement; however, the moduli of the P75 laminae in the transverse directions are 20–40% lower. On the other hand, the laminae reinforced with the high strength AS4 fibres have higher strengths in both the fibre and the transverse directions, with the tensile strengths being more than double those of the P75 laminae in both cases.

All values in Table 1 are taken from open literature,[30–33] except G_{23} and υ_{23} which were determined using theory of elasticity approach [27] from the properties of the fibre and the matrix, since values for these were not available in literature. The strength values in the Table 1 are the long-term values, which are taken to be 80% of the short-term static strength values [28] from literature to achieve a conservative design.

Due to the susceptibility of laminated composite tubes to micro-cracking,[34] it is necessary to use inner liners to avoid fluid leakage. The liner materials considered in this study include steel, titanium alloy, aluminium alloy and the thermoplastic PEEK. In the finite element modelling, a bilinear kinematic hardening material model is used for the metal liners and elastic material model for the PEEK. Load carrying capacity of the liner is taken into account in the design of the composite risers. The mechanical properties of the liner materials used in the finite element analysis (FEA) are given in Table 2.

The composites and the liner materials listed in Tables 1 and 2, respectively, give rise to eight practical material system combinations to be considered for the design. These are presented in Table 3.

In the fabrication of metal liners often autofrettage is employed, which is a technique in which the tube is subjected to an enormous internal pressure causing internal portions to yield and resulting in internal compressive residual stresses in the inner layers to increase the durability of the metallic liner as well as its resistance to stress corrosion cracking. However, the effect of autofretting is not considered in this paper.

Table 2. Mechanical properties of liner materials.

Liner materials	Density [kg/m^3]	Elastic modulus [MPa]	Poisson's ratio	Yield stress [MPa]	Ultimate stress [MPa]	Elongation at break [%]
PEEK	1300	3.64	0.4	120		
Steel (X80)	7850	207.0	0.3	555	625	5.9
Titanium (Ti-6Al-4 V)	4430	113.8	0.342	880	950	14.0
Aluminium (1953T1)	2780	71.0	0.3	480	540	7.5

Table 3. Material combinations considered in design.

Configuration	Fibre	Matrix	Liner material
1	AS4	PEEK	PEEK
2	P75	PEEK	PEEK
3	AS4	Epoxy	Steel
4	P75	Epoxy	Steel
5	AS4	Epoxy	Titanium
6	P75	Epoxy	Titanium
7	AS4	Epoxy	Aluminium
8	P75	Epoxy	Aluminium

3.2. Finite element model

For the design process, the stresses in the composite tubulars are determined through numerical modelling using ANSYS 13.0. Because the composite cylinder wall is quite thick, 3D solid elements (Solid 186) are employed in the FEA. The composite laminate is modelled with layered-solid elements and the liner with homogeneous solid elements. Perfect bonding between the liner and composite layers is assumed. The cylindrical tubular is constrained in the axial direction at one end and free at the other (see Figure 3). The rigid body motions of the cylinder are also constrained. Eighty elements were employed in the circumferential direction and 50 elements per metre in the axial direction based on convergence studies. The length and the inner diameter of the tubular are fixed (3 and 0.25 m, respectively); the outer diameter depends on the thickness selected. The design process essentially consisted of conducting analysis in ANSYS for the five design LCs with different thickness values for the composite layers and the liner and determining the Utilisation Factors (UF). The iterative procedure for selecting the thickness values, to arrive at minimum weight by bringing the maximum UF to 1.0 or just below it, is described in the next section.

3.3. Design LCs

The five local LCs [26] considered for the design are:

- LC 1 (Burst load): Internal pressure of 155.25 MPa with end effect (2.25 times the maximum internal pressure);
- LC 2 (Pure tension): Maximum tension force with a load factor of 2.25;
- LC 3 (Tension with external pressure): 2.25 times maximum tension with an external pressure of 19.5 MPa;
- LC 4 (Collapse): External pressure of 58.5 MPa (maximum external pressure with a load factor of 3); and

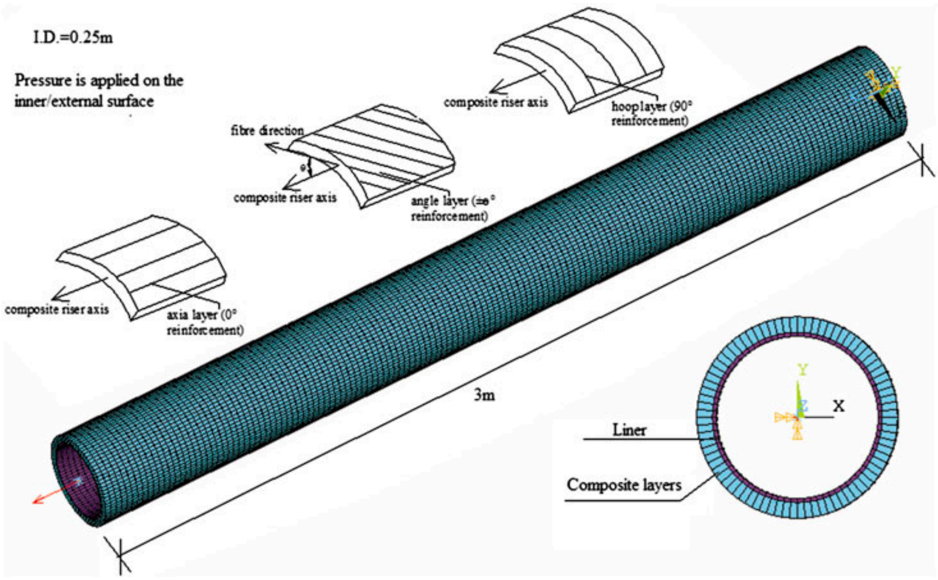

Figure 3. FEA model of the composite tube and coordinate system.

- LC 5 (Buckling): Buckling external pressure of 58.5 MPa (maximum external pressure with a load factor of 3).

In this study, the tension is calculated based on a design of 2000 m for the risers. Note that the effective weight is a function of the wall thickness (both liner and composite body) selected for the analysis. For the burst case, the end effect due to internal pressure is simulated by applying equivalent axial tension. The local buckling discussed herein refers to hoop buckling under external pressure (analysed using eigenvalue buckling analysis) since the applied top tension ensures that compressive axial loads are low throughout the riser, eliminating the possibility of axial buckling.[28] In the extreme case, the external pressure may cause a buckle to propagate along the pipeline; however, as long as the external pressure is less than the propagation pressure threshold, the buckle will not propagate.[2] Global buckling (such as upheaval buckling and lateral buckling) [35] which is a beam-mode buckling that is characterised by an amplitude and wavelength is out of the scope of current paper. For risers, the global buckling is mainly due to bending caused by lateral force. For subsea pipelines, an upheaval buckling may take place for a buried pipeline that lifts up due to excessive expansion,[35] whereas unburied pipes on the seabed can buckle laterally instead of vertically unless the lateral friction coefficients are very high. The driving force for lateral buckling is the compressive force induced by operational temperature and pressure.[35] In this paper, the focus is on the local design stage and hence only local buckling analysis under external pressure as suggested by Ochoa [28] is conducted. Note that in the local design stage, the design codes for deep sea risers only require static capacity to be checked; however, to ensure long-term durability of the structure, it will be necessary to test for resistance against long-term stress rupture by establishing a stress rupture curve with test results up to 10,000 h.

3.4. Design methodology

Two types of design are considered for the composite tubulars: The conventional orthogonal design, in which the laminate has reinforcements only in the axial and hoop directions alternately, and the tailored design, in which reinforcements in the axial, hoop and at other angles are considered. For the composite body, the ply stacking sequences and laminae fibre orientations are varied systematically for each material combination in Table 3.

The design process consists of determining the stress distribution in each layer using FEA for LCs 1–4 for each material combination with the selected thickness values. The failure criterion employed in the stress analysis is the maximum stress criterion for composite laminates,[27] in which the normal stresses in the fibre and transverse directions and the in-plane shear stress are compared to the longitudinal, transverse and shear strengths of the lamina. An eigenvalue buckling analysis is also conducted using the FE model to determine the buckling pressure for the configuration under investigation. An iterative procedure is employed to vary the liner and composite layer thickness, fibre orientations and stacking sequence until a maximum UF of 1.0 is achieved in all the layers of the composite for LCs 1–4 and for the buckling of the cylinder under external pressure (LC 5). It may be noted that the UF is defined as the ratio of actual stress (or load) to the allowable stress (or load). This gives the minimum weight required for each material combination considered for each type of design. It may be noted that the critical buckling pressure decreases with increasing tube length for short cylinders, but soon asymptotes to its minimum value. A convergence analysis conducted initially showed that for the composite tubes under consideration, the asymptotic value of critical pressure is reached when the tube length is 5 m; hence, all the buckling analyses in the iterative procedures were performed on riser segments of 5 m length.

3.4.1. *Methodology for conventional design*

The flow chart for the design methodology for the conventional design is shown in Figure 4(a). Once the design conditions and a combination of materials (fibre reinforcement, matrix and the liner) are selected (*step 1*), an initial estimate of the thicknesses required for the layers reinforced in the axial and hoop directions is determined based on membrane theory for the design burst pressure with end effect (*step 2*), assuming that the axial stress is carried by the axially reinforced layers and the hoop stress by the circumferentially reinforced ones as in netting theory. With this initial estimate of the thickness of composite layers and a guess value for the liner thickness, a 3D FEA of the model is conducted for only the burst case to determine UFs in each layer (*step 3*) to determine whether the thickness of layers – in the axial or hoop direction – should be increased (if the UF is greater than 1) or reduced (if the safety margin is too high). At the end of *step 3*, the thickness of axial and hoop layers is optimised for the burst condition for the liner thickness chosen. This procedure is repeated for different values of the liner thickness and the one which gives the minimum overall structural weight is selected (*step 4*). A similar process is repeated in *step 5*, but now considering all the LCs. At the end of this process, the minimum thicknesses of axial and hoop reinforced layers and the liner required to satisfy all five LCs are obtained.

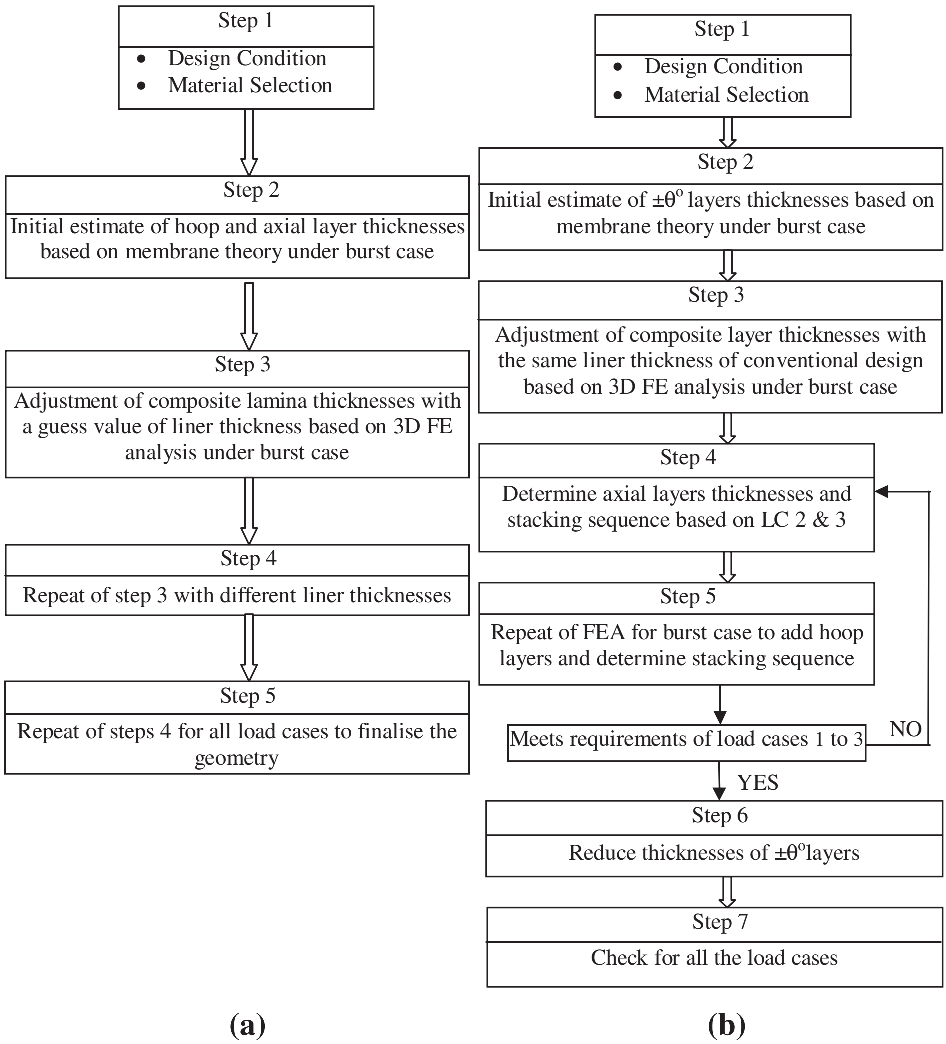

Figure 4. Flow charts for (a) conventional design with orthogonal plies and (b) tailored design including angle reinforcements.

3.4.2. *Methodology for design including angle plies*

The flow chart of the tailored design methodology including composite layers reinforced at angles other than 0° and 90° is shown schematically in Figure 4(b). *Step 1* in this design process is exactly the same as that of the conventional design process. In *step 2*, using the same liner thickness as determined by the conventional design, the initial optimum angle of reinforcement $\pm\theta°$ and the layer thicknesses are estimated based on the burst capacity using membrane theory. *Step 3* is similar to that of the conventional design, except that the stresses from the FEA are employed to re-estimate the thickness of layers in $\pm\theta°$ directions required to avoid failure. In *step 4*, the tension LC is employed to add axially reinforced layers to the angle ply laminate designed in *step 3*, to withstand the axial load. The burst case is analysed again to determine the thickness of hoop reinforced layers required to reduce the in-plane transverse stress in axial layers. These axially loaded layers are susceptible to transverse failure under burst pressure, due to having low transverse strengths (*step 5*). It is required to go through several iterations of *steps 4* and *5*, to converge on the minimum number of 0° and 90° layers to be added. The addition of the hoop and axially reinforced layers permits the reduction of the angle plies (*step 6*). Several iterations of *steps 3–6* are conducted to home in on the optimum thickness of the axial, hoop and angle plies required to withstand both the design burst and the design tension loads. In this iterative loop, variations in the stacking sequence of the laminate are also examined to determine the best combination of stacking sequence and thickness of plies, which will provide the least weight under these LCs. In the final step (*step 7*), the design is checked for all the LCs and the thickness of plies increased if required by the other LCs.

4. Results for AS4/PEEK riser with PEEK liner

All eight different material system combinations (Table 3) were analysed using the two iterative design methodologies to determine the optimum combination of ply orientations, stacking sequence and composite and liner thicknesses.

In order to illustrate the effect of introducing the angle plies and different stacking sequences, the results of the FEA of a typical case, that of AS4/PEEK composite body and PEEK liner which provide the least structural weight, obtained with the two design approaches, are compared below. The conventional design provided a 21 plies composite laminate $[90/(0/90)_{10}]$ with alternating hoop and axially reinforced layers having thicknesses of 1.85 and 1.165 mm, resulting in a total laminate thickness of 32 mm and with the PEEK liner having a thickness of 6 mm. The tailored design including the angle plies provided a 17 layer composite laminate $[0_3, (+52, -52)_5, 90_4]$ with the 0°, 90° and ±52° having thicknesses of 1.48, 1.64 and 1.30 mm, respectively. The total laminate thickness for the design including the angle plies is only 24 mm with the same 6 mm thickness for the liner, providing a 24% weight saving for the composite layers over the conventional design. It is also to be noted that the optimum angle of reinforcement for the angle plies was obtained as ±52° using the 3D FEA, not ±54.7° as predicted by netting theory. In this section, UFs in every composite layer are plotted for two typical LCs (burst case and tension with external pressure). The UFs for the PEEK liner for LCs 1–4 are 0.83, 0.11, 0.11 and 0.11 for the conventional design and 1.0, 0.20, 0.23 and 0.21 for the tailored design, respectively.

Figure 5(a) and (b) respectively shows the UFs in the fibre and transverse directions for LC 1 (burst load) for the all the layers in the conventional design configuration. The maximum UF in the fibre direction is 0.74 (layer 1 in Figure 5(a)), while the maximum UF in the transverse direction is 1.0 (layers 20 and 21 in Figure 5(b)). It is evident that under burst case, the in-plane transverse stresses are the most critical stresses and determine the min thickness of the composite AS4/PEEK with PEEK liner with only 0° and 90° reinforcements.

Figure 6(a)–(c) respectively shows the UFs in the fibre, transverse directions and in-plane shear for the all the layers for LC 1 (burst load) for the tailored design with additional angle plies and considering different stacking sequences. The maximum UF is 0.85 in the fibre direction (layer 14 in Figure 6(a)), 1.0 in the transverse direction (layer 3 in Figure 6(b)) and about 0.33 in shear (layer 4 in Figure 6(c)). In this case, also the in-plane transverse stresses are the most critical and determine the thickness of the composite layers.

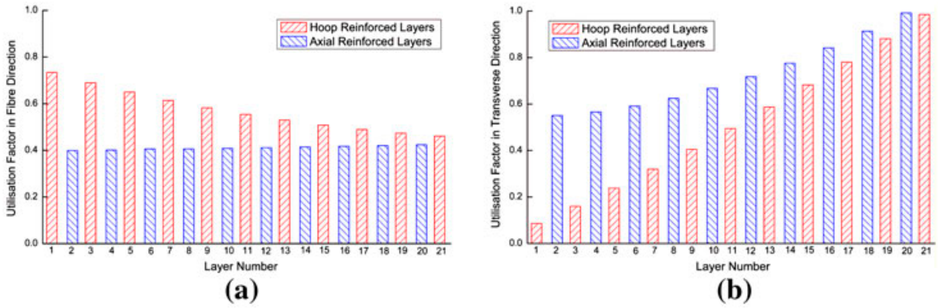

Figure 5. UFs of composite layers with 0° and 90° reinforcements under LC 1 for the AS4/PEEK with PEEK liner in (a) fibre direction and (b) transverse direction.

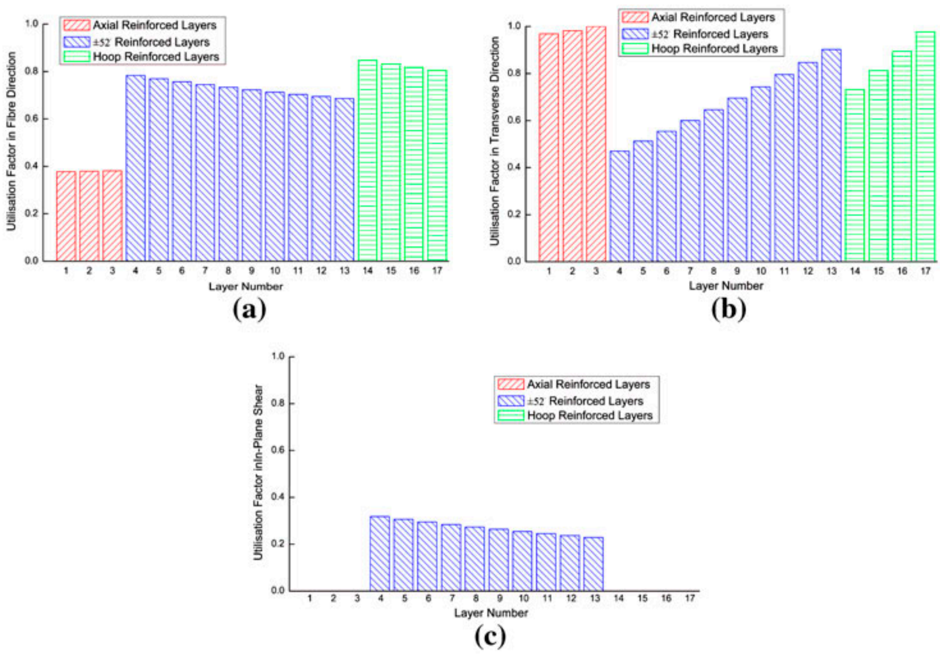

Figure 6. UFs of composite layers with 0°, ±52° and 90° reinforcements under LC 1 for the AS4/PEEK with PEEK liner in (a) fibre direction, (b) transverse direction and (c) in-plane shear.

Figures 7 and 8 respectively show the UFs under LC 3 for the conventional and the tailored designs, respectively. The maximum UF for this case for the conventional design is 0.46 (in transverse direction in layer 1, Figure 7(b)) and 0.86 for the tailored design (in transverse direction in layer 14, Figure 8(b)), both of which are smaller than the maximum UFs obtained under the burst case.

The results for the other LCs are similar, it can be seen the UFs in all the layers for LCs 2–4 are well below 1, indicating that for the AS4/PEEK composite with PEEK liner, LC 1 (burst pressure) is the most critical LC.

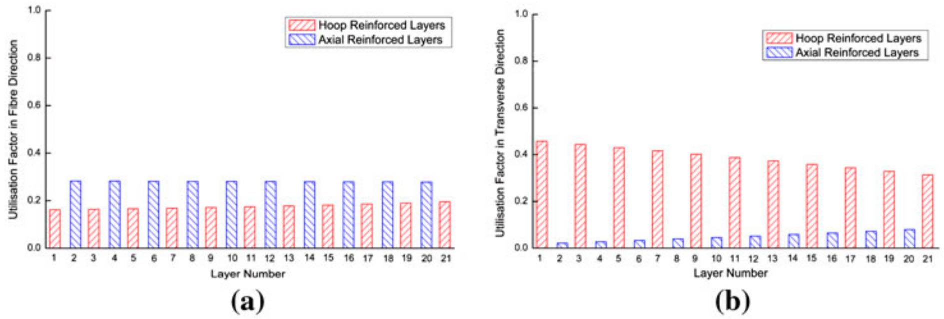

Figure 7. UFs of composite layers with 0° and 90° reinforcements under LC 3 for the AS4/PEEK with PEEK liner in (a) fibre direction and (b) transverse direction.

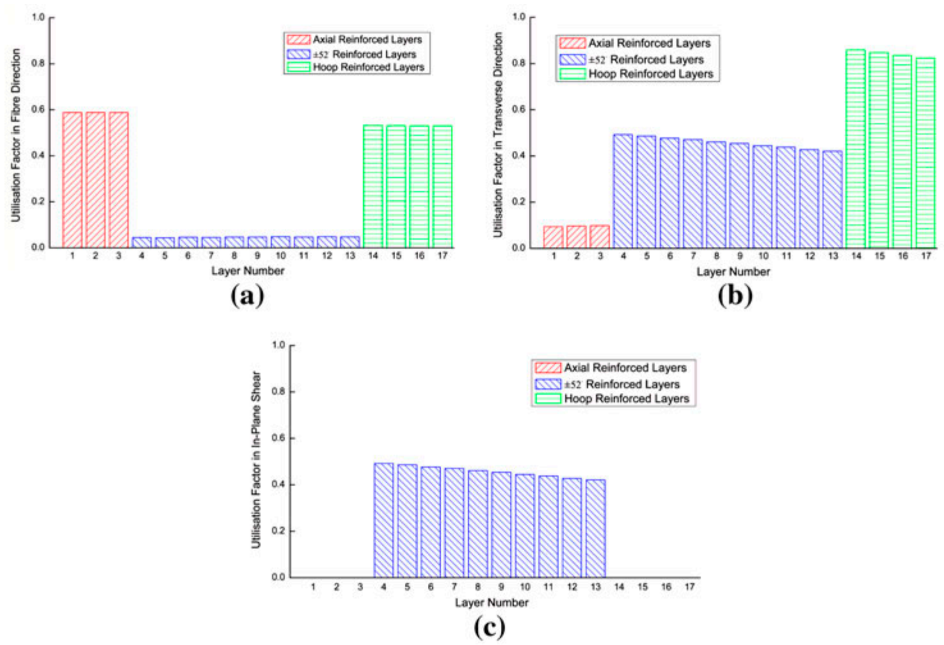

Figure 8. UFs of composite layers with 0°, ±52° and 90° reinforcements under LC 3 for the AS4/PEEK with PEEK liner in (a) fibre direction, (b) transverse direction and (c) in-plane shear.

It is also noticeable that the margins of safety are smaller in the tailored design than in the conventional design, indicating that it is more efficient. The final configurations of the two designs were also checked for buckling under external pressure (LC 5). The critical buckling pressures for the conventional design and the tailored design configurations were obtained as 186.4 and 59.6 MPa, respectively, both of which are higher than the design collapse pressure of 58.5 MPa.

It may be noted that for the burst case, the maximum UF in the transverse direction is close to 1.0 for both the conventional and tailored designs, while the UFs in fibre direction are well below 1.0. Thus, for the AS4/PEEK with PEEK liner, matrix cracking is the most critical failure mode and dictates the design. However, for other material combinations, such as P75/PEEK with PEEK liner, shown in the next section, fibre failure can become the most critical failure mode.

5. Results for P75/PEEK riser with PEEK liner

With the tailored design process presented in Figure 4(b), P75/PEEK with PEEK liner offers the geometry of the composite riser tubular with a 43 layer composite laminate with $[0_9, (+55.5, -55.5)_2, 90_{10}, (+55.5, -55.5)_{10}]$. The total laminate thickness for the tailored design is 86 mm with the same 6 mm thickness for the liner, providing a 26.1% structural weight saving over the conventional design. Under 155.25 MPa design internal pressure, the UF of PEEK liner is 0.63.

Due to space limitations, only the UFs under LC 1 (burst load) for the tailored design are presented here. Figure 9(a)–(c) shows the UFs under LC 1 for the P75/PEEK composite body with PEEK liner in the fibre, transverse directions and in-plane shear, respectively, for all the layers. The maximum UF is 1.00 in the fibre direction (layer 10 in Figure 9(a)), while the maximum UF in the transverse direction (layer 10 in Figure 9(b)) is 0.54 and in in-plane shear (layer 10 in Figure 9(c)) about 0.11. In this case, the stresses in fibre direction are the most critical, define the failure mode and determine the thickness of the composite layers.

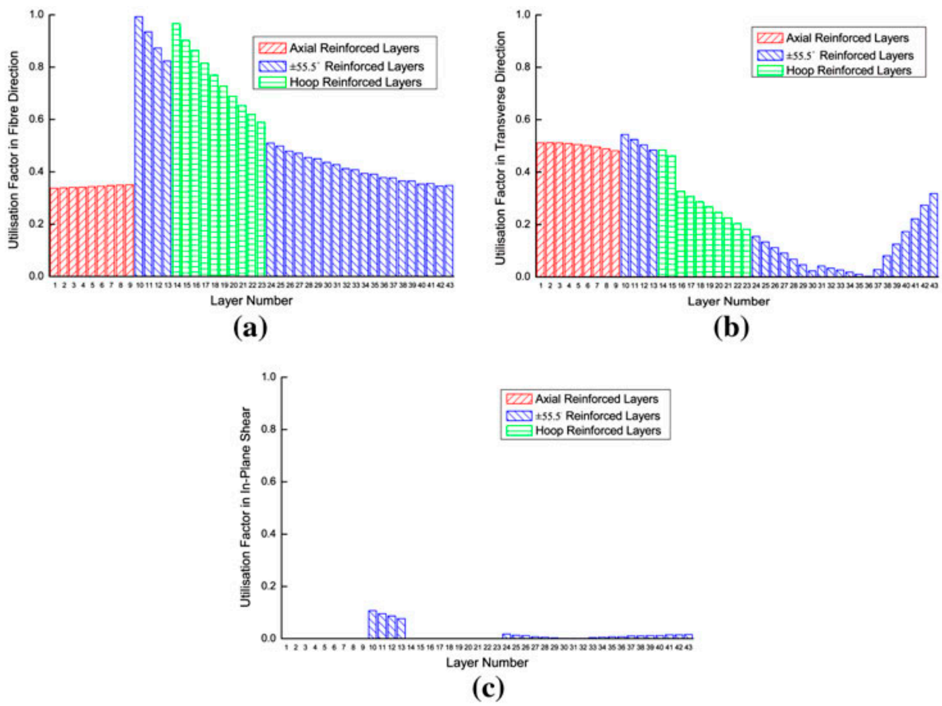

Figure 9. UFs of composite layers with 0°, ±55.5° and 90° reinforcements under LC 1 for the P75/PEEK with PEEK liner in (a) fibre direction, (b) transverse direction and (c) in-plane shear.

6. Consideration of design allowing matrix cracking

The maximum stress failure criterion used in the paper considers failures in the fibre direction, transverse direction and in-plane shear separately. The latter two are associated with matrix cracking. Therefore, the matrix cracking is included as one of the failure modes to be considered. For some material combinations, matrix cracking is the most critical failure mode, such as in the case of AS4/PEK with PEEK described in Section 4, whereas in other cases, such as that o P75/PEEK with PEEK liner (Section 5), fibre failure becomes the most critical. It is to be noted that the design standards require the composite riser to be designed to withstand the burst case without leakage assuming that the liner may have cracked, which means without any matrix cracking in the composite body. Hence, the design criteria used in this study does not allow matrix cracking.

However, in order to investigate whether the tailored design offers any weight advantage, if matrix cracking is permitted, an analysis has been conducted on the AS4/PEEK with PEEK liner allowing matrix cracking, i.e. considering that only fibre failure constitutes failure. The results show that if matrix cracking is permitted, the composite body can be thinner and therefore has lower weight. The tailored design with angle reinforcements still yield a configuration with lower weight than the conventional design, if matrix cracking is not included as a failure criterion.

Figure 10 compares the structural weights obtained for the AS4/PEEK riser with the PEEK liner, using the conventional and the tailored design approaches when matrix cracking is allowed and when it is prevented. It can be seen that with matrix cracking, both designs provide lower weight, about 69% of the design with no matrix cracking for the conventional design and 84% of the design with no matrix cracking for the tailored design. If matrix cracking is permitted, the tailored design still provides a weight saving, but only about 7% saving compared to the conventional design with matrix cracking.

7. Comparison of results

7.1. Comparison of structural weights

Similar analysis as described in Section 4 for the AS4/PEEK riser was carried out for the remaining seven configurations in Table 3, using both the conventional orthogonal

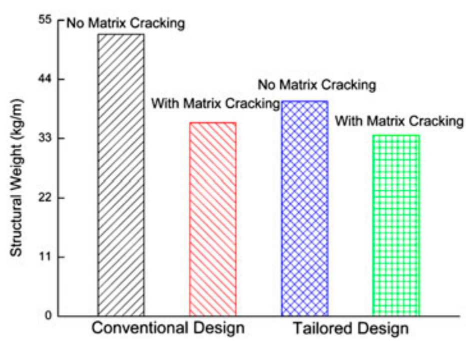

Figure 10. Comparison of structural weights of designs with and without matrix cracking permitted (AS4/PEEK with PEEK liner).

design and the tailored design including angle plies, to optimise their lay-ups for minimum structural weight. Figure 11 shows the comparison of the optimised structural weights, normalised with the structural weight of steel pipe with the same inner diameter required to meet the same design requirements, which was found to be 170 kg/m. The first eight bars in Figure 11 are for composite pipes reinforced with the AS4 fibre, while the last eight are for pipes reinforced with the P75 carbon fibre. The first four in each group are the minimum structural weights obtained with the conventional design using only axial and circumferential reinforcements, while the last four are results obtained using the tailored design which includes angle ply reinforcements. The first bar in each group of four is for the composite with PEEK matrix and PEEK liner, while the remaining are for the epoxy-based composites with the liners of steel, titanium and aluminium alloy. From Figure 11, it is apparent that all the composite risers, except the P75/PEEK composite with PEEK liner, offer substantial structural weight savings compared to the steel riser. In general, reinforcement with the high strength AS4 fibres is found to be much more beneficial than reinforcement with the high stiffness P75 fibres. While the P75/PEEK pipes with PEEK liners are heavier than steel, the same pipes with metallic liners have structural weights lower than that of steel. On the other hand, when reinforced with AS4 fibres, the pipe with the thermoplastic liner has lower weight than those with metallic liners. In fact, the AS4/PEEK composite pipe with the PEEK liner has the least structural weight of all material combinations. It is also clear that in every case the tailored design with the angle reinforcements included offers greater weight savings than the conventional design with only axial and circumferential reinforcements. The structural weight comparison with different design methods using AS4 fibre reinforcement is given in Table 4. In the case of the AS4/PEEK composite pipe with the PEEK liner, the conventional design gives a normalised weight of 0.31, while the tailored design including the angle plies results in a normalised weight of only 0.235, a weight saving of over 76% over steel and 24% over the conventional design using the same composite materials. For the composite riser with steel, titanium and aluminium liners, the structural weight savings using the tailored design method are 23, 23 and 25% over the conventional design, respectively. Considering the

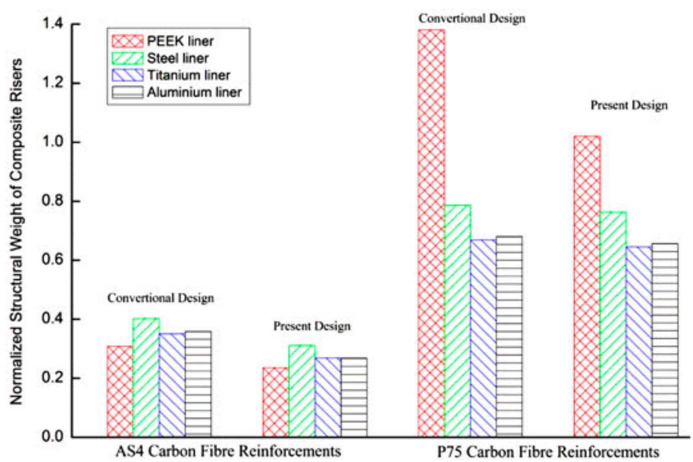

Figure 11. Comparison of normalised structural weight for the optimised designs.

Table 4. Comparison of structural weights of optimised configurations with and without angle ply reinforcements.

AS4/PEEK with PEEK liner (kg/m)			AS4/epoxy with steel liner (kg/m)			AS4/epoxy with titanium liner (kg/m)			AS4/epoxy with aluminium liner (kg/m)		
0° and 90°	±52° and 90°	weight saving	0° and 90°	±53.5° and 90°	weight saving	0° and 90°	±53° and 90°	weight saving	0° and 90°	±53.5° and 90°	weight saving
52.4	39.9	24%	68.2	52.6	23%	59.6	45.7	23%	60.9	45.4	25%

effect of liner materials, the use of metallic liners show a consistent trend of decreasing weight with decreasing specific stiffness (E/ρ) (steel, Ti and Al, in that order).

7.2. Comparison of thicknesses

The penalty for the savings in weight with the composite construction is an increase in the overall pipe thickness. Figure 12 shows the comparison of the overall wall thicknesses of the eight configurations designed using both approaches. The thicknesses are normalised with respect to that of the steel riser. It is clear that in every case, the total wall thickness is higher than of steel. Once again the laminates reinforced with the high stiffness P75 carbon fibres fare much worse, with the P75/PEEK pipe with the PEEK liner having thicknesses four to five times that of steel. It is clear that that P75/PEEK composite with PEEK liner is the least desirable material combination, with higher weights and significantly higher thicknesses than steel. Figure 12 also shows that the tailored design with the angle plies provides lower thickness in every case (which accounts for their lower weights in Figure 11) compared to the conventional design. The AS4/PEEK with PEEK liner is once again the best performer, with the least thickness of all the configurations considered.

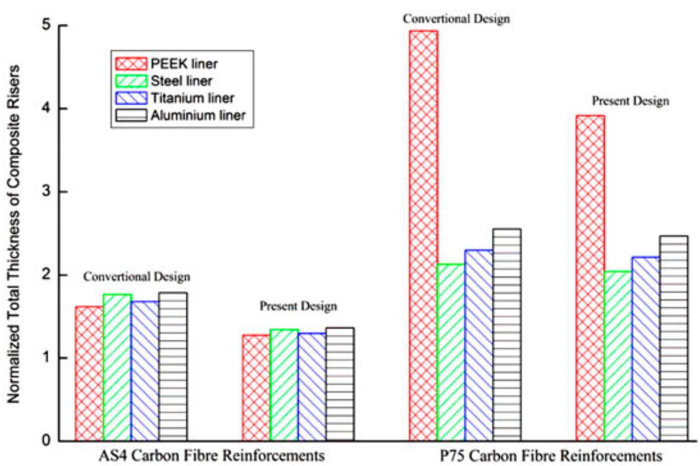

Figure 12. Comparison of normalised thicknesses for the optimised designs.

7.3. *Effect of reinforcement fibres*

One of the results from the study is the finding that composite risers reinforced with high strength AS4 fibres have a much lower weight than those reinforced with high modulus P75 fibres. This can be attributed to the fact that the AS4 fibres have twice the strength of the P75 fibres, but only about half the stiffness. Hence, the AS4-reinforced composite body can carry a much higher load, or in other words require a much lower thickness, compared to the P75 riser, resulting in significantly lower structural weight.

It is also seen that when the AS4 fibres are employed in the composite with the PEEK liner provides the least weight, whereas when the P75 fibres are used for reinforcement, the composite bodies with metallic liners have lower weight than with PEEK liner. This is because when AS4 reinforced epoxy is employed for the composite body with metallic liners, the liner thickness reduces to about one third of that of the PEEK liner, but does not change its weight significantly. However, the thickness of the composite body increases appreciably, resulting in 10–30% higher overall structural weights for the AS4/epoxy risers with metallic liners. On the other hand, when P75 fibres are used with metallic liners, the thickness of the composite body reduces by about 50% compared to that of the P75/PEEK body, while the liner thickness nearly double. This reduces the overall weight of P75 reinforced risers with metallic liners by 25–35% compared to the structural weight of the P75/PEEK body with PEEK liner.

7.4. *Role of liner in load bearing*

Employing the PEEK liner appears to reduce the weight further than that of metallic liners only when the high strength carbon fibre (AS4) reinforcement is used; the use of PEEK does not provide weight savings when the high modulus fibres (P75) are used. It is also found that when the metal liner is employed, the loads are jointly carried by the liner and composite body before the liner yields and after the liner yields, loads are mainly carried by the composite body. In contrast, when a PEEK liner is employed, the loads are mainly carried by the composite body, since the stiffness of the PEEK liner is much smaller than that of the fibre-reinforced composite body.

8. Conclusion

The design of composite riser tubular with various laminate structures and material combinations was performed with the objective of determining whether the inclusion of additional angle plies, different liner thickness, different stacking sequences and different material combinations can generate greater weight savings than that obtained with the conventional axial and hoop reinforcement design. Both conventional and tailored design offer significant weight savings compared to the steel riser. The results also show that the use of high strength carbon fibre reinforcement is much more beneficial than employing high modulus carbon fibre reinforcement. The AS4/PEEK composite with PEEK liner offers the least weight with smallest thickness among all configurations considered. The tailored design including layers with inclined reinforcements offers additional weight savings of up to 25% compared to that using conventional orthogonal reinforcement.

For deep sea risers, cyclic fatigue and stress rupture are also important design considerations. However, these aspects are out of the scope of the paper, since the objective of the present work is to demonstrate how greater weight savings can be achieved by a tailored design of the composite lay-up as opposed to conventional design for the local LCs. It may also be noted that the laminate configurations optimised for minimum structural weight in this local design study are then employed in the global design of the composite riser, taking into consideration the global mechanical and environmental loads on the riser for global analysis and structural verification, which is the second stage of the composite riser design. The global design, which is an essential step to complete the design, is presented in a separate future publication. From the further global design study, the optimised geometries developed here successfully satisfy the global design requirements.

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