Local Design of Composite Riser under Burst, Tension, and Collapse Cases

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1 Introduction

In order to transport offshore oil and gas from the subsea wellhead to the production platform on the surface, production risers are indispensable. The riser is a tubular structure, usually made up of many segments, to which a top tension is normally applied, to eliminate compressive stresses and maintain its vertical position. The weight of the riser and consequently the top tension required increases with increasing depth. These are usually the critical factors limiting the number of risers attached to each platform and thereby its production capacity. Hence, if the weight of individual risers can be reduced, production capacity can be improved, resulting in significant financial benefits.

Most of the production risers currently used in offshore engineering are made of high grade steel. Due to their desirable mechanical properties and low density of advanced fibre reinforced polymer (FRP) composites, it has for some time now been recognised that their application for manufacture of deep sea oil production riser systems would lead to considerable weight savings as well as facilitate extraction of oil and gas from greater depths [1-2]. Further, FRP composites also have better thermal insulation, corrosion and fatigue resistance than steel. The use of FRP composites also offers a wider range of design possibilities, with different matrix and fibre reinforcement combinations, variations in fibre orientations, different stacking sequences and different liner materials.

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 (IFP) and Aerospatiale of France undertook a project to evaluate composite offshore tubulars [3]. Their design included 9.6mm glass fibre circumferential layers, 7.3mm carbon fibre composite longitudinal layers and 1.1mm Buna inner layer. In the mid nineties, the National Institute of Standards and Technology (NIST) Advanced Technology Programs (ATP) developed and tested composite riser tubulars used for application at depths between 1000m and 1500m [4]. A demonstration composite drilling riser joint (a tube segment) was installed in field on Heidrun Tension Leg Platform (TLP) in July 2001[5]. ConocoPhillips, Kvaerner Oilfield Products and ChevronTexaco jointly funded a composite riser project in March 2003 [6]. The purpose was to replace a few steel joints with composite joints on the Magnolia TLP. The projected structural weight saving over steel for a 63 ft joint was around 48%.

More recently, Doris Engineering, Freyssinet, Total and Soficar cooperated to develop carbon fibre reinforced thermoplastic tubes [7]. In July 2009, Airborne Composite Tubulars, MCS Advanced Sub-sea Engineering and OTM Consulting organised a Joint Industry Programme [9] to prove the concept of a thermoplastic composite riser, but no details are currently available in open literature.

While most previous designs of composite risers [3-6] employed fibre reinforcements only in the axial and hoop directions, the co-operative venture by Doris Engineering and others [7] introduced fibre reinforcements at an angle of $\pm 55^{\circ}$ in an attempt to improve efficiency and further reduce weight. Using netting theory it can be shown that $\pm 54.7^{\circ}$ is the most efficient angle for filament winding a cylindrical pressure vessel which has a hoop stress to axial stress ratio of 2:1, since it does not require a reinforcement in any other direction [8]. Netting theory assumes that all the loads are carried by the fibres located in each layer and no stresses are developed in transverse direction. However, if the stiffness in the transverse direction is taken into account, stresses develop transverse to the fibres, which can lead to matrix failure. Hence, for a laminated composite, $\pm 54.7^{\circ}$ might not represent the most efficient direction for fibre reinforcement under internal pressure with end effect and the minimum laminate thickness depends on the ratios of the transverse (and shear) stiffness and strength to those in the fibre direction. Further, for a production riser with top tension, the ratio of the hoop stress to axial stress is not 2:1, hence the use of the angle of $\pm 54.7^{o}$ is no longer the fully justifiable.

In this paper, the effects of fibre orientations and stacking sequences on the weight of the composite riser are investigated using the composite laminate theory that takes into account of the transverse properties of the composite material. The structural weight of a typical riser joint obtained with the fibre orientations and the stacking sequence optimised for structural efficiency 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 two different reinforcement materials, viz., High Strength (HS) carbon fibre and High Modulus (HM) carbon fibre) and two different matrices, epoxy and Poly Ether Ether Ketone (PEEK). Since laminated composite materials are susceptible to fluid leakage due to micro-cracking, it is normal to use liner(s) for composite risers. The liner materials considered in the design include steel, titanium alloy, aluminium alloy and PEEK. The design study is conducted using the four main load cases recommended for local design of subsea riser systems [10].

2 Material Selection and Properties

The eight different material system combinations that have been studied are presented in Table 1. The mechanical properties for the liner materials are listed in Table 2. The 3-D mechanical properties of unidirectional composite lamina are given in Table 3. All values in Table 3 are taken from open literature, except G_{23} and υ_{23} which are determined using micromechanics [12]. First ply failure, using maximum stress criterion in in-plane longitudinal, transverse and shear strength is employed to determine the required thickness. The strength values used are the long-term values, taken to be 80% of the short-term static strength values [13] .

3 Finite Element Model

The stress analysis is conducted through numerical modelling ANSYS 12. Since the composite cylinder is relatively thick, 3-D Solid 186 elements are employed in the finite element analysis (FEA). The cylindrical tubular is taken to be fixed at one end and free at the other. The four local load cases considered in the study are: (1) Burst pressure of 155 MPa with end effect (2.25 times the maximum internal pressure); (2) Pure tension - maximum tension force with a load factor of 2.25; (3) Tension combined with external pressure (2.25 times maximum axial tension and external pressure of 19.5 MPa); and (4) Collapse - maximum external pressure (19.5 MPa) with a load factor of 3.

The length and internal diameter used for the FEA model are 3m and 0.25m, respectively. Eighty elements in the circumferential direction and fifty elements per metre in axial direction are used for the mesh. Solid 186-homogenous elements are used for the liner and Solid 186-layered elements for composite laminate.

4 The Design Process

The design process consists of determining the stress distribution in each layer using FEA for every load case for each material combination and assumed thickness values. A Matllab programme was written to determine the Factors of Safety (FS) for the first ply failure using maximum stress criterion. Then an iterative procedure using the FEA and Matlab code is employed to vary the layer thickness until a minimum FS of 1 is achieved.

Since the objective is to determine the weight savings that can be achieved by tailoring the reinforcements in the composite layers over the conventional method of employing reinforcements only in orthogonal (axial and hoop) directions, each material configuration is designed using both approaches. Since it has been found that the burst pressure case is the predominant loading that determines the thicknesses of the composite layers and the liner, this load case is first employed for an initial estimate of the thicknesses in both procedures. The flow chart for the iterative procedure using the conventional design methodology (with only orthogonal reinforcements) is shown in Fig.1. Once the design conditions and material configuration are selected (Step 1), an initial estimate of the thicknesses of the layers reinforced in the axial and hoop directions is made using membrane theory for the condition of burst pressure with end effect (Step 2). The FEA is performed with these initial estimates for the composite layers and a guess value for the liner thickness for only the burst case to determine the stresses and the factors of safety and the thicknesses of the layers with axial and hoop reinforcements increased or decreased depending on whether the FS is above or below 1 (Step 3). At the end of step 3, the thickness of axial and hoop layers are optimised for the burst condition for the value 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). Noting that the preceding steps have considered only the burst pressure loading, the thicknesses determined from step 4 are employed in the FEA to analyse the tubular for all four load cases. If factor of safety smaller than 1 is obtained for any of the other three load cases, the thicknesses of composite layers are increased until a minimum FS of 1 is achieved. At the end of this process the minimum thicknesses of axial and hoop reinforced layers and the liner material required to satisfy all four load cases are obtained.

The flow chart of the new design methodology including composite layers reinforced at angles other than 0^0 and 90^0 is shown schematically in Fig.2. Once the design conditions and material configuration are selected (Step 1), using the same liner thickness as determined by the conventional design, the initial optimum angle of reinforcement $\pm\theta^\circ$ and the layer thicknesses are estimated based on the burst capacity (Step 2). 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 $\pm\theta^\circ$ directions required to avoid failure. In Step 4, the tension load case 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 (Step 5). It is required to go through several iterations of steps 4 and 5, to converge on the minimum number of 0^0 and 90^0 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 to 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, different stacking sequences are also examined. In the final step (Step 7), the design is checked for all the load cases and the thickness of plies increased if required by the other two cases.

5 Stress Distributions in AS4/Epoxy Composite Riser with Titanium Liner

All eight different material system combinations (Table 1) were analysed using the two iterative design methodologies to determine the optimum combination of ply orientations, stacking sequence and composite and liner material thicknesses, which provides the least weight.

To illustrate the effect of introducing the angle plies and different stacking sequences, the results of the finite element stress analysis of a typical case, that of AS4/Epoxy composite body and Titanium liner (Configuration 5 in Table 1), obtained with the two design approaches for the burst pressure case, are compared below.

Figs.3 (a) and 3 (b) respectively show the factors of safety in the fibre and transverse directions, for the all the layers for the design using the conventional method. It can be seen that the minimum factor of safety in the fibre direction is 1.7 (layer 1 in Fig.3 (a)), while the minimum factor of safety in the transverse direction is 1.0 (layers 20 and 21 in Fig.3 (b)). So it is clear that in this case the in-plane transverse stresses are the most critical and determine the minimum thickness of the composite of the AS4/Epoxy with Titanium liner, with only 0^0 and 90^0 reinforcements. Figs.4 (a), 4 (b) and 4 (c) respectively show the factors of safety in the fibre and transverse directions and in in-plane shear for the all the layers for the design based on the new approach, with additional angle plies. The minimum factor of safety is 1.65 in the fibre direction (layer 14 in Fig.4 (a)), 1.0 in the transverse direction (layers 3 and 17 in Fig.4 (b)) and about 2.16 in shear (layer 4 in Fig.4 (c)). In this case also the in-plane transverse stresses are the most critical and determine the thickness of the composite layers. However, the total thickness and hence the weight of the design including angle reinforcements is much lower than that with only orthogonal reinforcements, as will be seen in the next section. The following general trends were observed in comparing the stress distributions in all eight configurations: (1) The substantial difference in the stiffnesses of the liner and the composite layers significantly influences the stress distribution and the failure process (2) In the case of HS-CFRP (AS4 reinforcement), the failure occurs due to in-plane transverse stress or shear stress exceeding their allowable values, while in the case of HM-CFRP (P75 reinforcement), it is the stress along the fibre direction that causes failure of the plies.

6 Structural Weight and Thickness Comparison

Fig.5 (a) shows the comparison of the optimum structural weights, normalised with respect to the weight required for a steel riser to carry the same loads, obtained with the conventional and the new design approach for the eight configurations listed in Table 1. The thicknesses of the composite designs (including the thickness of the liners) are shown in Fig.5 (b), once again using the thickness of steel riser as benchmark.

From Fig.5 (a) it is immediately apparent that all the composite risers (except the P75/PEEK composite with PEEK liner) offer substantial weight savings compared to the steel riser, especially those reinforced with AS4 fibre. On the other hand, Fig.5 (b) shows that all the composite risers have higher thicknesses than the steel riser; however the increase in thickness is lower for those reinforced with AS4. Thus reinforcement with high strength fibres (AS4) appears to be much more beneficial than that with the high modulus fibre (P75). 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 appear to be beneficial to the weight when the high modulus fibres (P75) are used.

With both high modulus and high strength fibre reinforcements, the new design methodology, including layers with inclined fibre orientations appears to offer significant weight savings over the traditional orthogonally reinforced design. Of all the 8 configurations considered in both the approaches, the least weight obtained is that of the AS4/PEEK composite with PEEK liner with angle plies included (0.235 times that of steel). This is 24% lower than the weight of the conventional design (0.31 times that of steel) using the same material combination. The AS4/PEEK composite with angle reinforcements and PEEK liner also has the least overall thickness among the composite tubulars (only 28% more than that of steel).

7 Conclusions

The local 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 can generate greater weight savings than that obtained with the conventional axial and hoop reinforcement design. The results show that while all composite material configurations with metallic liners considered offer weight savings over steel tubulars, the use of high strength carbon reinforcement is much more beneficial than employing high modulus carbon fibre reinforcement. The AS4/PEEK composite with PEEK liner offers the least weight and least thickness, among all configurations considered. The new design with the additional layers with inclined reinforcements offers weight savings of up to 24% compared to that using conventional orthogonal reinforcement.

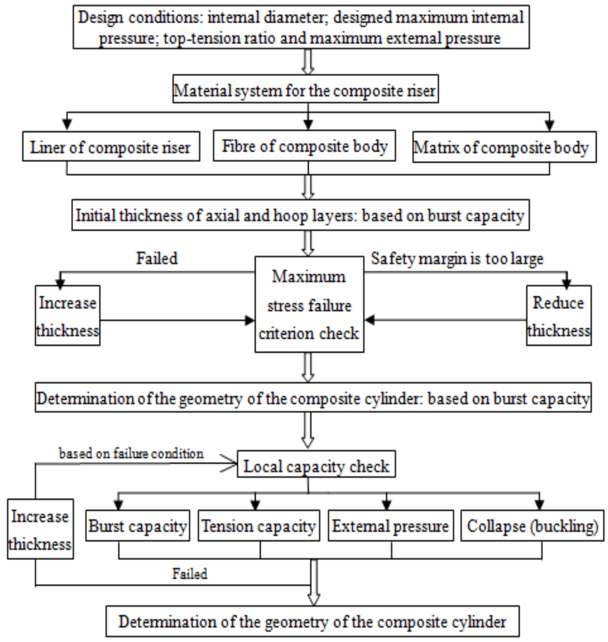


Fig.1: Flow chart for conventional design with only axial and hoop reinforcements

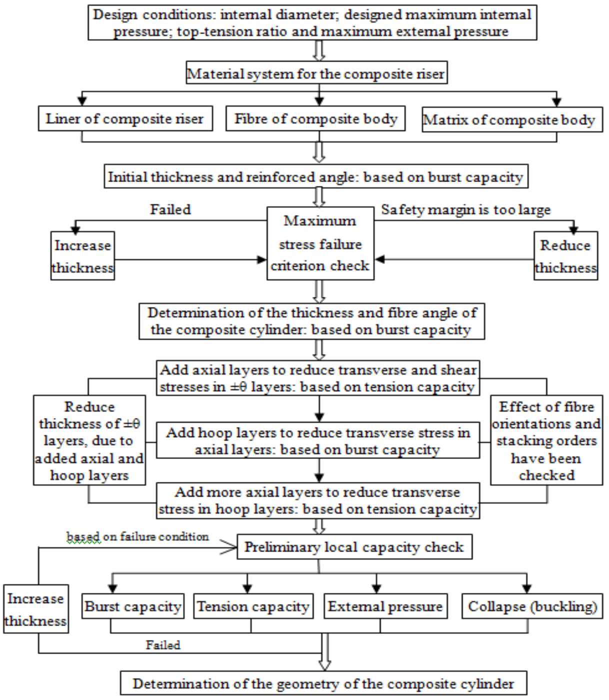
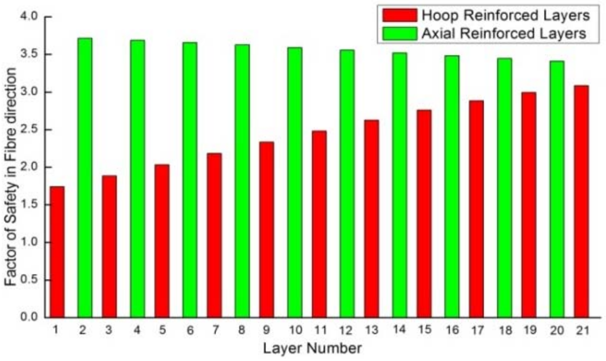
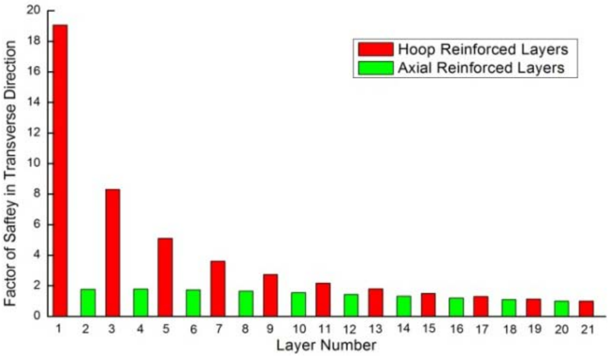


Fig.2: Flow chart for current design with inclusion of layers with inclined reinforcement

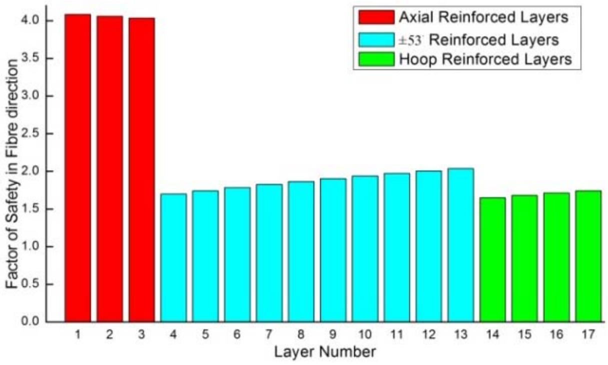


(a)

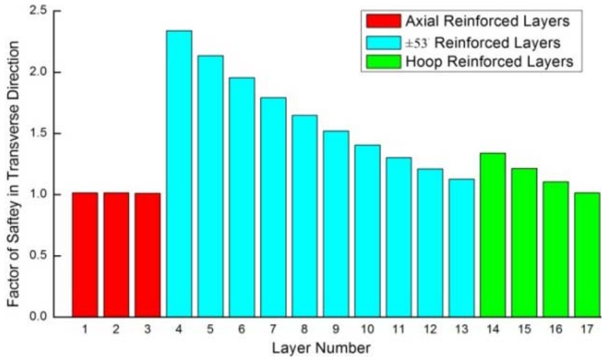


(b)

Fig.3: Factors of safety of composite layers with 0° and 90˚ reinforcements for burst case for the AS4/epoxy/titanium riser in (a) fibre direction (b) transverse direction



(a)



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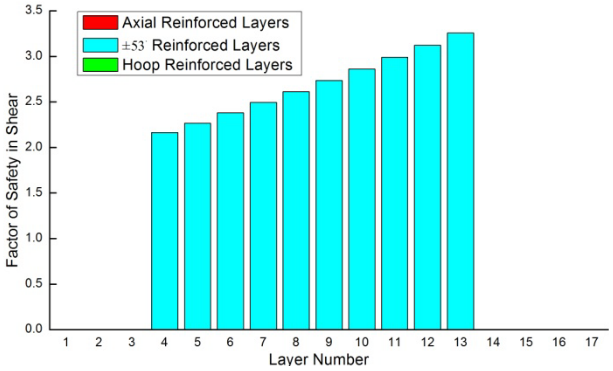
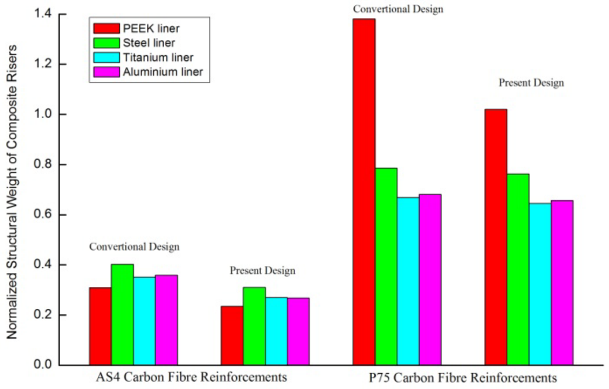
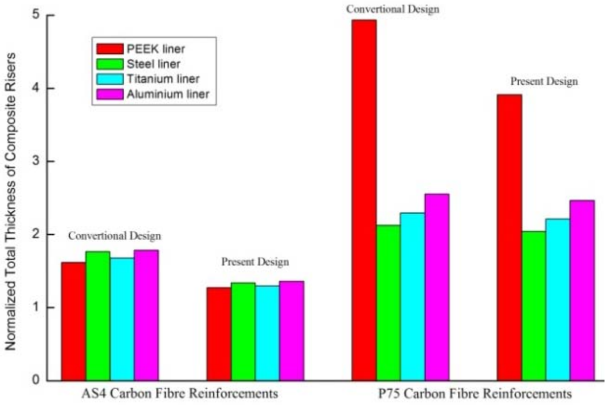


(c)

Fig.4: Factors of safety of composite layers with 0°, ±53˚ and 90˚ reinforcements for burst case for the AS4/epoxy/titanium riser in (a) fibre direction (b) transverse direction (c) shear



(a)



(b)

Fig.5: Comparison of (a) structural weight and (b) total thickness.

Table 1. 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

Table 2. Mechanical properties of liner materials

Material	ρ $[kg/m^3]$	E [MPa]	υ	σ_{yield} [MPa]	σ_{ultimate} [MPa]	Elongation [%]
PEEK	1300	3.64	0.4	120		
Steel	7850	207.0	0.3	555	625	5.9
Titanium	4430	113.8	0.342	880	950	14
Aluminium	2780	71.0	0.3	480	540	7.5

Table 3. Mechanical properties of composite laminae 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	0.6	1530	135.4	9.37	4.96	3.20	0.32	0.46	1732	1256	49.4	167.2	71.2
P75-Epoxy	0.6	1776	310.0	6.60	4.1	2.12	0.29	0.70	720	328	22.4	55.2	176
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-PEEK	0.55	1773	280.0	6.70	3.43	1.87	0.30	0.69	668	364	24.8	136	68

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