World Academy of Science, Engineering and Technology
International Journal of Mechanical and Mechatronics Engineering
Vol:6, No:12, 2012

Design of Composite Risers for Minimum Weight

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***Abstract*—**The use of composite materials in offshore engineering for deep sea oil production riser systems has drawn considerable interest due to the potential weight savings and improvement in durability. The design of composite risers consists of two stages: (1) local design based on critical local load cases, and (2) global analysis of the full length composite riser under global loads and assessment of critical locations. In the first stage, eight different material combinations were selected and their laminate configurations optimised under local load considerations. Stage two includes a final local stress analysis of the critical sections of the riser under the combined loads determined in the global analysis. This paper describes two design methodologies of the composite riser to provide minimum structural weight and shows that the use of off angle fibre orientations in addition to axial and hoop reinforcements offer substantial weight savings and ensure the structural capacity.

***Keywords*—**Composite Riser; Composite Tubular; Finite Element Modelling; Global Design; Local Design; Offshore Engineering.

Open Science Index, Mechanical and Mechatronics Engineering Vol:6, No:12, 2012 publications.waset.org/4236.pdf

I. INTRODUCTION

THE production riser is an indispensable component of offshore oil and gas exploitation structure to transport the extracted fluids from the subsea wellhead to the production platform on sea surface. 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 and the number of risers that can be attached to the platform. Hence, due to the desirable mechanical, thermal insulation and durability properties and low density of advanced fibre reinforced polymer (FRP) composites, it has been widely recognized that their use for the manufacturing of deep sea oil production riser systems would lead to considerable weight savings and therefore the operation cost of existing platforms and will also facilitate extraction of oil and gas from greater depths [1, 2]. 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.

In the past three decades, there have been several attempts to design and fabricate riser segments out of FRP composites [3-7].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 ±55^o in an attempt improve efficiency and further reduce weight based on netting theory which assumes that all the loads are carried by the interwoven fibres located in each layer and no stresses develop transverse to the fibres and ±54.7^o is the most efficient reinforcement angle for a filament wound thin cylindrical pipe under internal pressure with end effect (burst case for production riser design) which has a hoop stress to axial stress ratio of 2:1. However, in a real laminated composite construction, these assumption and conclusion are no longer valid. We need to separately evaluate optimum reinforcement directions for thick laminated tubes under specific load cases (LCs) to achieve the maximum weight reduction.

In this paper, both local and global design stages have been considered. In the local design stage, the effects of liner and layer thicknesses, 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 by "new" design method 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 materials selected for this study include 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 [8]. The liner materials considered in the present design include steel, titanium alloy, aluminium alloy and PEEK. The design study is conducted using the five main load cases recommended for local design of subsea riser systems by the American Bureau of Shipping (ABS) [9]. In finite element modelling it is necessary to use 3D (solid) layered elements to accurately determine the stresses in each layer in the local design stage.

In the global design stage, operational and environmental loads are required arising from top tension force, platform motion, hydrostatic pressure, gravity, buoyancy, wave and current loads on the whole length riser. Noting that a typical offshore riser has a length of over 2000m, if the 3D layered

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elements are applied the same as in local design stage, it would involve the use of several millions of 3D layered elements, in order to maintain appropriate aspect ratios. A non-linear finite element analysis taking into account the large deformations of the riser under global loading employing several millions of layered 3D elements will be prohibitively time consuming and resource intensive. It is therefore pragmatic to conduct the global design stage of composite risers in two steps. (1) The geometric configuration determined in the local design stage, is employed in the global analysis, in which the moments and forces along the length of the riser due to global functional and environmental loads are determined and (2) a structural verification of the critical sections of the riser is performed. The load cases consider the different combinations of operational and environmental loads applied to the whole length riser including platform motion, top tension force, hydrostatic pressure, gravity, buoyancy, wave and current loads are presented schematically in Fig. 1.

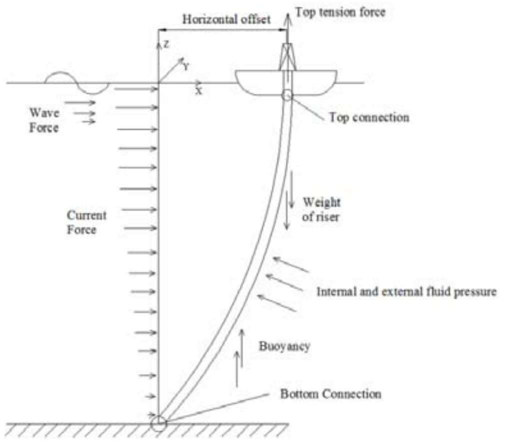


Fig. 1 Loads on a top-tension riser system

II. LOCAL DESIGN OF COMPOSITE TUBULARS FOR MINIMUM WEIGHT

The previous study [10] 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. If the laminate reinforcement is chosen as 54.7° based on netting theory, this would make the liner much the thicker and the overall weight of the tube higher. For example, an AS4/PEEK composite tube designed using netting theory, the thickness of a PEEK liner required to carry the maximum design tensile load will be 12 times higher than if the laminate was designed to take both internal pressure and tension, resulting in a tube that is three times heavier.

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 "traditional" orthogonal design (axial and hoop reinforcements) employed so far, as well as for the "new" design using fibre reinforcements in other orientations in additional to the axial and hoop directions.

A. Material Selection and Properties

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 I. 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_1, τ_{12}), where the subscripts 1, 2 and 12 stand for the fibre direction, transverse direction and in-plane shear, respectively. 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. The mechanical properties of the liner materials used in the finite element analysis (FEA) are given in Table I as well.

The composites and the liner materials listed in Tables I give rise to eight practical material system combinations to be considered for the design. These are presented in Table II.

TABLE I
MECHANICAL PROPERTIES OF UNIDIRECTIONAL FRP REINFORCED LAMINA AND LINER 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]	υ_{12}= υ_{13}	υ_{23}	σ_1^T [MPa]	σ_1^C [MPa]	σ_2^T [MPa]	σ_2^C [MPa]	τ_{12} [MPa]	Yield stress [MPa]	Ultimate stress [MPa]	Elongation at break [%]
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			
PEEK		1300	3.64				0.40							120		
Steel		7850	207.0				0.30							555	625	5.9
Titanium		4430	113.8				0.342							880	950	14.0
Aluminium		2780	71.0				0.30							480	540	7.5

TABLE II
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

B. Finite Element Model

In the local design process, the stresses in the composite tubulars are determined through numerical modelling using ANSYS 13.0. 3D solid elements (Solid 186) are employed in the finite element analysis. The composite laminate is modelled with layered-solid elements and the liner with homogeneous solid elements (see Fig. 2). The cylindrical tubular is constrained in the axial direction at one end and free at the other. The rigid body motions of the cylinder are also constrained. Eighty elements were employed in the circumferential direction and fifty elements per metre in the axial direction based on convergence studies. The length and the inner diameter of the tubular are fixed (3m and 0.25m respectively); the outer diameter depends on the thickness selected. The minimum factor of safety (FS) has to be larger than 1.0 in this stage.

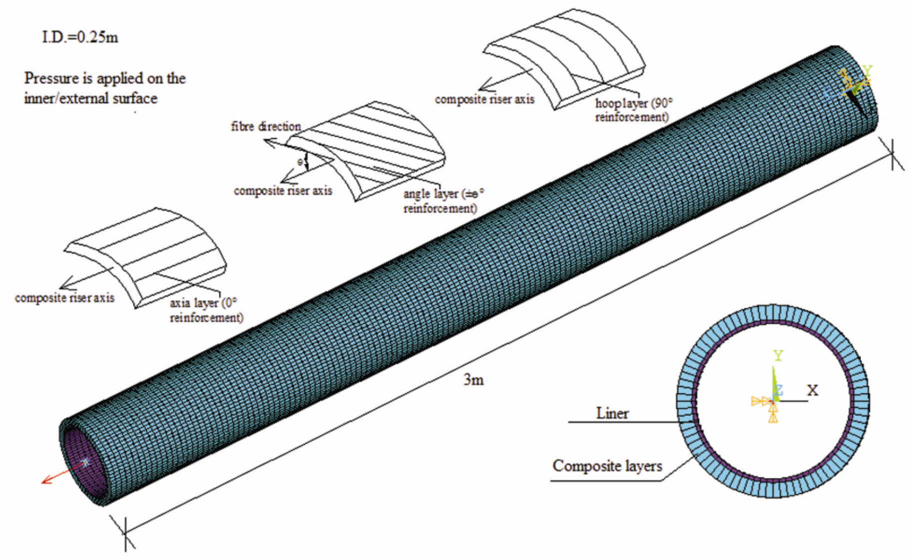


Fig. 2 FEA model of the composite tube and coordinate system

C. Design Load Cases

The five local load cases [9] considered for the design are:

Load Case 1 (Burst load): Internal pressure of 155.25 MPa with end effect (2.25 times the maximum internal pressure);

Load Case 2 (Pure tension): Maximum tension force with a load factor of 2.25;

Load Case 3 (Tension with external pressure): 2.25 times maximum tension with an external pressure of 19.5 MPa;

Load Case 4 (Collapse): External pressure of 58.5 MPa (maximum external pressure with a load factor of 3); and

Load Case 5 (Buckling): External buckling 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 2000m for the risers. Note that the effective weight is a function of the wall thickness selected for the analysis. For the burst case, the end effect due to internal pressure is simulated by applying equivalent axial tension.

D. 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 new 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 and thicknesses are varied systematically for each material combination in Table II.

The design process consists of determining the stress distribution in each layer using FEA for every load case for each material combination with the selected thickness values. The factor of safety for each layer is determined using maximum stress criterion. Failure is determined based on first ply failure. An iterative procedure is employed to vary the liner and composite layer thickness, fibre orientations and stacking sequence until a minimum FS of 1 is achieved, which gives the minimum weight required for each configuration considered for each type of design.

1) Methodology for Conventional Design

The flow chart for the design methodology for the conventional design (laminate with only orthogonal, axial and hoop reinforcements) is shown in Fig. 3.

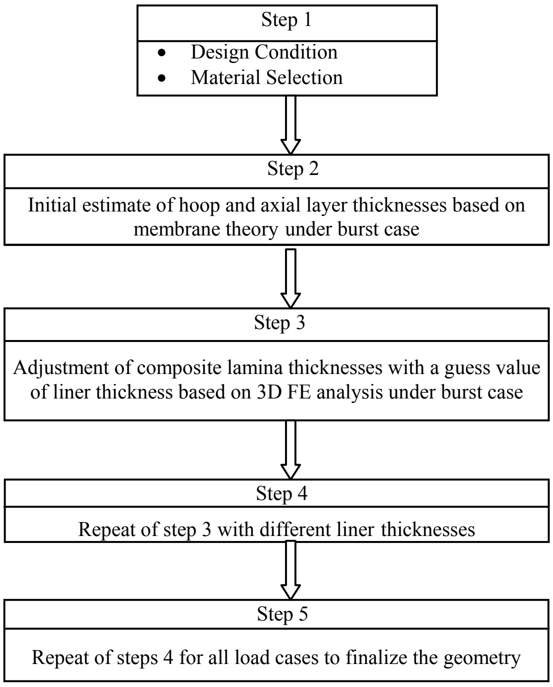


Fig. 3 Flow charts for conventional design with orthogonal plies

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 are 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 finite element analysis of the model is conducted for only the burst case to determine factors of safety in each layer and compared to the allowable stresses (*step 3*) to determine whether the thickness of layers – in the axial or hoop direction – should be increased (if the FS is less than 1) or reduced (if the safety margin is too high). At the end of step 3, the thickness of axial and hoop layers are 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 five load cases. At the end of this process the minimum thicknesses of axial and hoop reinforced layers and the liner required to satisfy all five load cases are obtained.

2) Methodology for Design Including Angle Plies

The flow chart of the new design methodology including composite layers reinforced at angles other than 0^o and 90^o is shown schematically in Fig. 4.

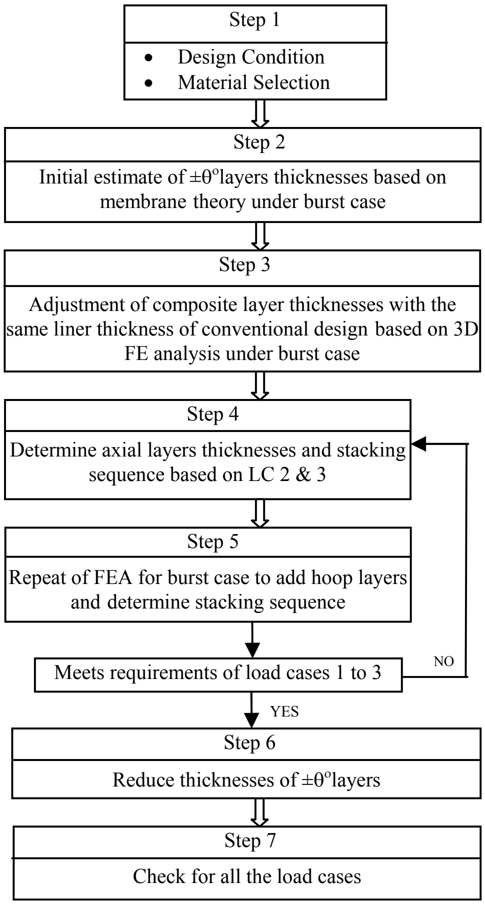


Fig. 4 Flow charts for new design including angle reinforcements

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 $\pm\theta^o$ 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 $\pm\theta^o$ 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. 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^o and 90^o 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, 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 load cases. 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 load cases.

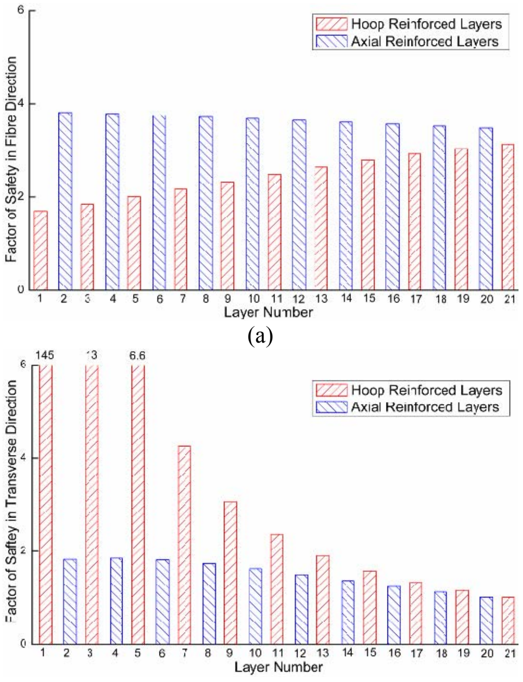
III. LOCAL DESIGN RESULTS FOR AS4/EPOXY RISER WITH ALUMINIUM LINER

All eight different material system combinations (Table II) 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 finite element analysis of a typical case, that of AS4/epoxy composite body and aluminium liner (Configuration 7 in Table II), obtained with the two design approaches for load case 1 (burst) 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 2.25mm and 1.525mm, resulting in a total laminate thickness of 40mm and with the aluminium liner having a thickness of 2mm. The new design including the angle plies provided a 18 layer composite laminate [0$_4$, (+53.5,-53.5)$_{5,}$ 90$_4$] with the 0^{o}, 90^{o} and $\pm 53.5^{o}$ having thicknesses of 1.62mm, 1.88mm and 1.60mm respectively. The total laminate thickness for the design including the angle plies is only 30mm with the same 2mm thickness for the liner, providing a 25% 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 $\pm 53.5^{o}$ using the 3D finite element analysis, not $\pm 54.7^{o}$ as predicted by netting theory. In this section, factors of safety in every layer are plotted for a typical load cases (burst case). The factors of safety for the aluminium liner for load cases 1 to 4 are 1.12, 3.05, 2.80 and 2.84 for the conventional design and 1.11, 1.66, 1.34 and 1.47 for the new design, respectively.

Figs. 5(a) and 5(b) respectively show the factors of safety in the fibre and transverse directions for load case 1 (burst load) for the all the layers in the conventional design configuration. The minimum factor of safety in the fibre direction is 1.7 (layer 1 in Fig. 5(a)), while the minimum FS in the transverse direction is 1.0 (layers 20 and 21 in Fig. 5(b)). It is evident that under burst case the in-plane transverse stresses are the most critical stresses and determine the minimum thickness of the composite AS4/epoxy with aluminium liner with only 0^{o} and 90^{o} reinforcements. Layer 1 is the innermost composite layer in these figures.

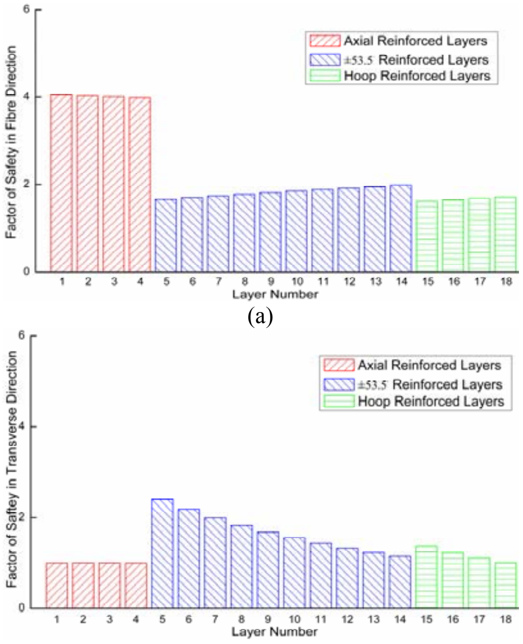
Figs.6(a), 6(b) and 6(c) respectively show the factors of safety in the fibre, transverse directions and in-plane shear for the all the layers for load case 1 (burst load) for the new design with additional angle plies and considering different stacking sequences. The minimum FS is 1.6 in the fibre direction (layer 15 in Fig. 6(a)), 1.0 in the transverse direction (layer 4 and layer 18 in Fig. 6(b)) and about 2.1 in shear (layer 5 in Fig. 6(c)). In this case also the in-plane transverse stresses are the most critical and determine the thickness of the composite layers.



(a)

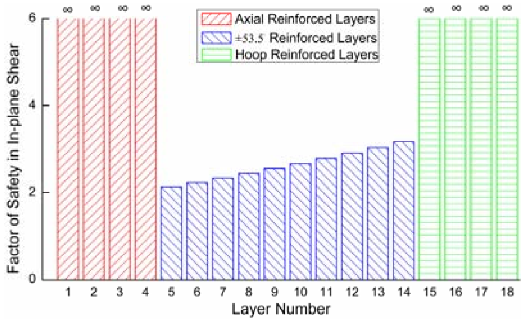
(b)

Fig. 5 Factors of safety of composite layers with 0° and 90° reinforcements under load case 1 for the AS4/epoxy with aluminium liner in (a) fibre direction, and (b) transverse direction



(a)

(b)



(c)

Fig. 6 Factors of safety of composite layers with 0°, ±53.5° and 90° reinforcements under load case 1 for the AS4/epoxy with aluminium liner in (a) fibre direction, and (b) transverse direction, and (c) in-plane shear

In general, it can be seen the factors of safety in all the layers for load cases 1 to 4 are above 1.0 for the AS4/epoxy composite with aluminium liner. It is also noticeable that the margins of safety are smaller in the new design than in the conventional design, indicating that it is more efficient. The final configurations of the two designs were also checked for buckling (load case 5) under external pressure. The critical buckling pressures for the conventional design and the new design configurations were obtained as 349.3MPa and 148.1MPa, respectively, both of which are higher than the design collapse pressure of 58.5 MPa.

IV. COMPARISON OF LOCAL DESIGN RESULTS

Similar analysis as described in section III for the AS4/epoxy-aluminium riser was carried out for the remaining seven configurations in Table II, using both the orthogonal design and the new design including angle plies, to optimise their lay-ups for minimum structural weight. Fig. 7 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 170kg/m. The first eight bars in Fig. 7 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 new 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.

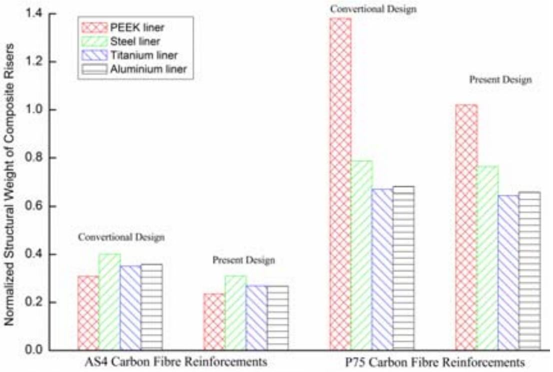


Fig. 7 Comparison of normalized structural weight for the optimized designs angle reinforcements

From Fig. 7, 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. 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. From Fig. 7, it is also clear that in every case the new 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 III.

TABLE III
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°	0°, ±52° and 90°	Weight Saving	0° and 90°	0°, ±53.5° and 90°	Weight Saving	0° and 90°	0°, ±53 ° and 90°	Weight Saving	0° and 90°	0°, ±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%

In the case of the AS4/PEEK composite pipe with the PEEK liner, the new design including the angle plies results in a structural weight saving of about 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 new design method are 23%, 23% and 25% over the conventional design, respectively. Considering the 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). 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.

V. GLOBAL ANALYSIS OF COMPOSITE RISER

After the local design, the next stage of composite riser design is global analysis to determine forces and moments at critical locations under the global loads acting on the riser.

A. *Finite Element Model*

The whole length of the composite riser is modelled in ANSYS13.0 using pipe element 288 with the option ocean loads, which provides the application of wave and current loading. Pipe 288, being a long one dimensional element, can cover the 2000m length of riser with a relatively small number of elements. Further it supports anisotropic material properties, although stresses in individual layers cannot be extracted. A total of 2127 elements were used in this study. In order to consider the dynamic effect of the environmental loads and platform motion, large displacement nonlinear dynamic analysis option is chosen.

While composite materials are employed for the standard joints (segments of the riser) making up most of the length (over 95% of all the length) of the riser (Fig. 8), the tension joint at the top, first three standard riser joints at the top (around the sea level) and stress joint at bottom were still retained as metallic, employing high grade steel (X80).

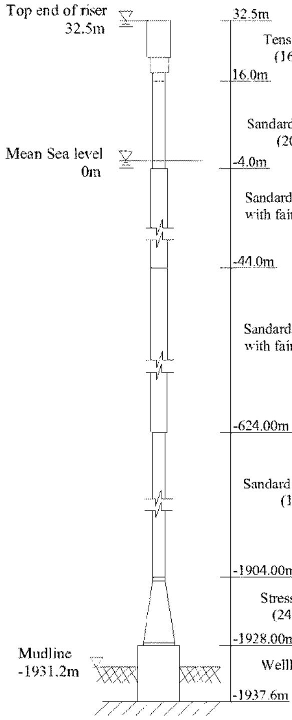


Fig. 8 Composite riser configuration

B. *Effective Properties of Composite Pipe Elements*

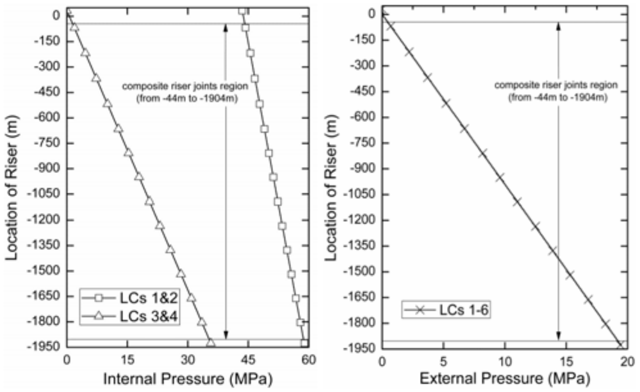
For the material properties of the composite pipe elements used in the global analysis, the 3D homogenous effective properties of the layered composite configuration obtained in the local analysis were determined. The theory and equations of 3D effective properties employed in this study are based on formulations by Sun and Li [11]. Here, three most promising material systems are selected for the global analysis in this study: AS4/PEEK body with PEEK liner and AS4/epoxy body with titanium or aluminium liners. The effective 3D elastic constants determined used in global analysis of the composite tubular are provided in Table IV. The subscripts x, y, z refer to axial, hoop and radius directions, respectively. However, we have to note, for a composite laminate, the effective moduli in tension and bending, $E_{\_tension}$ and $E_{\_bending}$, are different. The theoretical method to predict the 3D effective engineering constants can be used only for the tension modulus. To account for the different value of the modulus in bending, static analysis of FEA models of the selected lay-ups with solid185 (layer brick) and elbow290 (composite pipe) under pure bending are compared with the results of the FEA model using pipe 288 with effective engineering constants. If the difference between $E_{\_tension}$ and $E_{\_bending}$ is less than 5%, the average value is employed in the global analysis. Otherwise, both $E_{\_tension}$ and $E_{\_bending}$ are used in global analysis to determine the worst case.

C. *Global Load Cases on the Composite Riser*

The global design load cases are the combinations of different categories of environmental loading and riser conditions (Fig. 1). Here, it is based on the environmental situation of Gulf of Mexico [12-14] and given in Table V.

D. *Global Analysis Results for AS4/epoxy Riser with Aluminium Liner*

All three different material system and geometry combinations were analysed using the effective 3D properties of the composite riser. To illustrate the results, this section presents the global analysis results for various combinations of tension, bending, shear force and pressure due to the different global design load cases for the case of AS4/epoxy composite body with aluminium liner with material properties and thickness combinations as determined by the local analysis.



(a) (b)

Fig. 9 (a) Internal pressure for load cases LC1 to LC4 and (b) external pressure for load cases LC1 to LC6

The variations of internal and external pressures as functions of height along the length of the riser are shown in Figs. 9(a) and 9(b) for the various load cases, LC1 to LC6. It may be noted that the pressure variations are independent of materials used and are thus the same for all material combinations considered.

TABLE IV
3D EFFECTIVE PROPERTIES OF COMPOSITE TUBULAR USED IN GLOBAL ANALYSIS

Name	$\rho_{effective}$ [kg/m^3]	$E_{x\_tension}$[GPa]	$E_{x\_bending}$[GPa]	E_y [GPa]	E_z [GPa]	G_{xy} [GPa]	G_{xz} [GPa]	G_{yz} [GPa]	υ_{xy}	υ_{xz}	υ_{yz}
AS4/PEEK-PEEK liner (0°/±52°/90°)	1513.3	29.70		50.28	9.59	16.44	2.46	2.75	0.251	0.378	0.284
AS4/Epoxy-Ti liner (0°/±53°/90°)	1700.8	40.50	36.50	66.25	12.01	22.84	4.10	4.35	0.275	0.344	0.272
AS4/Epoxy-Al liner(0°/±53.5°/90°)	1599.8	41.40	37.20	64.12	11.92	20.57	4.07	4.28	0.254	0.349	0.293

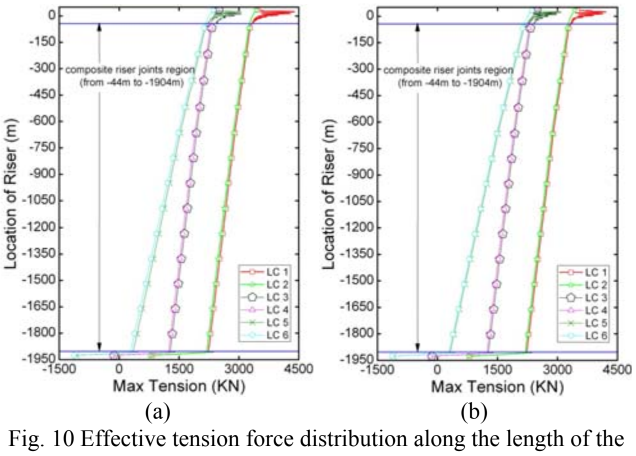
TABLE V
GLOBAL DESIGN LOAD CASES FOR THE RISER SYSTEM

Load Cases	Riser Condition	Fluid Density (kg/m^3)		Internal Pressure (MPa)[1]		Sea Water Density(kg/m^3)	Design Environment	Mean TLP Movement (m)	Tension Ratio
		Annulus	Tubing	Annulus	Tubing				
LC1	Shut-in with leak[3] under Hurricane	800	NA	58.6	NA[2]	1030	100 year hurricane	115.2	2
LC2	Maximum Production with leak[3]	800	NA	58.6	NA[2]	1030	100 year loop current	172.7	2
LC3	Well killed[4] 1	1860	NA	35.7	NA[2]	1030	100 year hurricane	115.2	1.5
LC4	Well killed[4] 2	1860	NA	35.7	NA[2]	1030	100 year loop current	172.7	1.5
LC5[*]	Shut-in under Hurricane	0	800	0	58.6	1030	100 year hurricane	115.2	1.2+end effect of external pressure
LC6[*]	Maximum Production	0	800	0	58.6	1030	100 year loop current	172.7	1.2+end effect of external pressure

[1] Internal pressure at the bottom end of riser is the maximum internal pressure.
[2] NA = no tubing applied.
[3] For the load cases with leak, all the pressure and effect of internal fluid on the riser wall with no tubing is considered.
[4] For the well killed situation, production tubing is removed and mud inserted into the whole riser annulus is considered.
[*] For load cases 5 and 6, the production tubing takes effects of the weight and pressure in annulus.

The tension force, bending moment and shear force distributions estimated from the global analysis conducted using FE modelling for load cases LC1 to LC6 are presented in Figs. 10-12, respectively. The blue horizontal lines in these figures indicate the top and bottom of the composite riser section, at depths of 44m and 1904m, respectively. Note that in designing the composite riser, we are only concerned about the tension, bending moment and shear force magnitudes within this region.

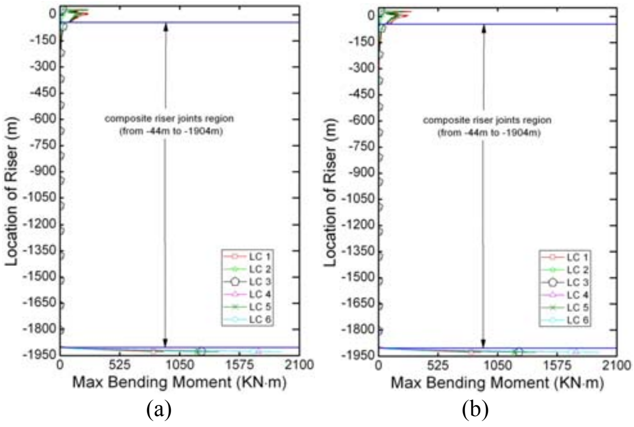
Fig. 10 shows the effective tension force distribution along the full length of the riser. It is clear that the maximum tension force of magnitude 3335.7kN in the composite section of the riser occurs under load case LC1 at the top end under tension modulus.



(a) (b)

Fig. 10 Effective tension force distribution along the length of the riser for load cases LC1 to LC6 with (a) bending modulus and (b) tension modulus

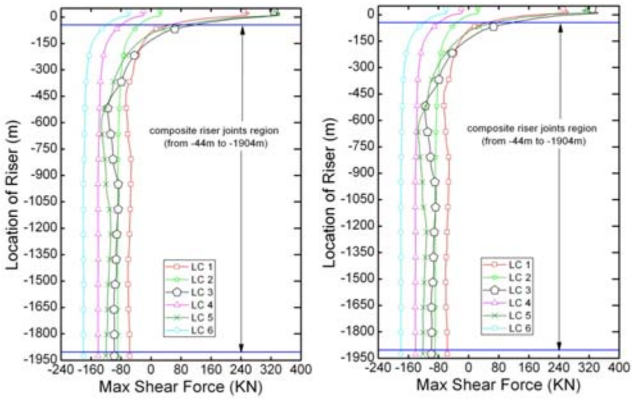
Fig. 11 shows the bending moment distribution along the full length of the riser. The maximum bending moments in the composite section of the riser occur at the top and bottom ends, with values of 61.2kN·m under LC1 at the top and 77.3kN·m under LC4 at the bottom end both with tension modulus. It may be noted that the bending moments are much higher in the metallic stress joints at the bottom, reaching up to around 2000kN·m at the bottom in load cases LC4 and LC6.



(a) (b)

Fig. 11 Bending moment distribution along the length of the riser for load cases LC1 to LC6 with (a) bending modulus and (b) tension modulus

Fig. 12 shows the shear force distribution along the full length of the riser. The maximum shear force (179.9kN) in the composite region occurs under LC6 at the bottom end under tension modulus.



(a) (b)

Fig. 12 Shear force distribution along the length of the riser for load cases LC1 to LC6 with (a) bending modulus and (b) tension modulus

It is clear that in the composite joints region, the internal pressure and external pressure increase from top to bottom, the tension force decreases from top to bottom, the maximum bending moment occurs at the top or bottom joint under different load cases and the maximum shear force occurs at the top or bottom joint under different load cases. Hence, it can be said the top and bottom joints are the most critical locations.

VI. STRUCTURAL CAPACITY VERIFICATION OF AS4/EPOXY RISER WITH ALUMINIUM LINER

After the determination the most critical locations and the critical load combinations at these locations, structural verification of these composite riser sections under different combinations of tension force, pressure, shear force and bending moments identified as critical load conditions in global analysis is followed.

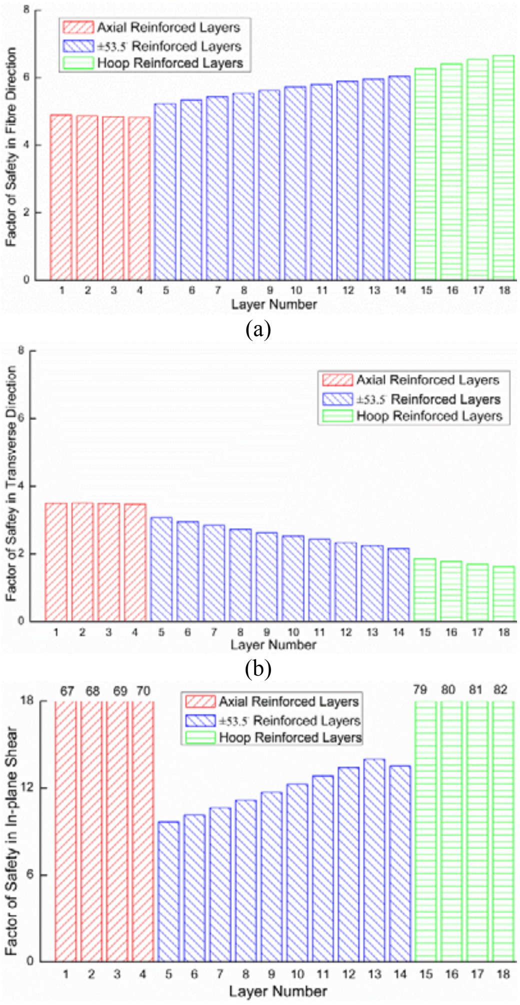
Stress analysis is again conducted using the FEA model of the local pipe section (short length pipe with 4.5m) as shown in Fig. 2 for the most critical load combinations given in Table VI. Typical results from the stress analysis of the AS4/epoxy riser with aluminium liner for one of the load combinations (LC1_top) are presented below for illustration.

TABLE VI
CRITICAL LOAD COMBINATIONS AND LOCATION FROM GLOBAL ANALYSIS

Load Case	Location	Max Tension (kN)	Internal Pressure (MPa)	External Pressure (MPa)	Max Shear Force (kN)	Max Bending (kN·m)
1	top	3335.7	44.3	0.7	52.1	61.2
	bottom	2251.8	58.7	19.2	56.8	47.4
2	top	3263.1	44.3	0.7	40.8	10.9
	bottom	2206.5	58.7	19.2	88.8	69.4
3	top	2386.3	1.8	0.7	119.0	44.8
	bottom	1290.5	35.3	19.2	98.8	54.5
4	top	2299.4	1.8	0.7	88.9	5.5
	bottom	1249.0	35.3	19.2	140.8	77.3
5	top	2212.3	0	0.7	87.4	51.8
	bottom	370.6	0	19.2	121.0	24.2
6	top	2152.0	0	0.7	128.2	5.7
	bottom	307.4	0	19.2	179.9	34.2

The local design did not take into account the forces and moments caused by global environmental and functional loads considered in the global analysis. Further, this stage is also employed for structural capacity verification, with larger factors of safety required by the standards. A minimum factor of safety of 1.53 is required for the composite laminae,1.74 for the PEEK liner and 1.68 for titanium and aluminium liners [15] under all the local force combinations obtained from the global analysis. Noting that the shear force at the end will algebraically add to the bending moment distribution along the length of the model, the stresses generated using both clockwise and anti-clockwise moments and the shear and tension loads are compared at one common location x_1 (1m from the top) and another location x_2 (x_2 has to be calculated) for the different load combinations.

The factors of safety obtained under load case LC1_top (see Table VI) are plotted as the example. The FS of in-plane longitudinal stress, in-plane transverse stress and the in-plane shear stress in all the layers are presented in Figs. 13(a), 13(b) and 13(c), respectively. Layer 1 is the innermost composite layer in these figures.



(c)

Fig. 13 Factors of safety of composite layers with 0°, ±53.5˚ and 90˚ reinforcements under combined LC1_top for the AS4/epoxy with aluminium liner in (a) fibre direction, and (b) transverse direction, and (c) in-plane shear

The minimum factor of safety obtained for the liner for this load case is 1.79. The minimum factors of safety for the stresses in the fibre direction (Fig. 13(a)) is 4.82 in the axially reinforced layers (0°) (layer 4). The minimum factors of safety for the transverse stress (Fig. 13(b)) are 1.62 in the 90° layers (layer 18). The factors of safety in shear in all the layers for this case were over 9.5, as seen in Fig. 13(c). Thus the minimum factor of safety under load case LC1_top is 1.62, occurring due to stresses in the transverse direction in layer 18 (reinforced in hoop direction) in the composite body.

VII. COMPARISON OF GLOBAL DESIGN RESULTS

Table VII shows the minimum factors of safety for the liner and composite body for all three material combinations and the critical load case in which it occurs. From the results presented in Table VII, it can be seen that all the geometry configurations developed for minimum weight in the local design, successfully withstand the global loads, providing factors of safety just above the values required by the standards. For all material combinations, the least factor of safety is obtained in the outermost composite lamina for the stresses in the transverse direction. The minimum factor of safety is 1.64, 1.57 and 1.62 respectively for the AS4-PEEK with PEEK liner, and the AS4/epoxy with titanium and aluminium liners. In the case of AS4/epoxy with titanium liner, the minimum FS is only 2.5% over the specified requirement of 1.53 for the composite body. It may also be noted that the top joint (segment) of the composite riser is the most critical region and that in all cases the minimum factor of safety occurs under load case LC1, the shut-in condition with 100 year hurricane, which has the highest effective top tension of and large bending moment.

TABLE VII
FACTORS OF SAFETY IN LINER AND COMPOSITE LAYERS FOR THE RISER CONFIGURATIONS STUDIED

Material Combination	Liner		Composite Layers- Fibre Direction			Composite Layers- Transverse Direction			Composite Layers– In-Plane Shear		
	FS	LC	FS	Layer	LC	FS	Layer	LC	FS	Layer	LC
AS4-PEEK(0°-52°-90°)	2.96	LC2_B	3.04	14	LC6_B	1.64	17	LC1_T	5.79	13	LC3_T
AS4-Ti(0°-53°-90°)	1.97	LC1_T	4.37	3	LC3_T	1.57	17	LC1_T	3.94	13	LC3_T
AS4-Al(0°-53.5°-90°)	1.79	LC1_T	4.82	4	LC1_T	1.62	18	LC1_T	4.56	14	LC3_T

Minimum FS required: 1.53 for composite layers, 1.74 for PEEK liner and 1.68 for metallic liners [15]

VIII. 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 new 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 new design including layers with inclined reinforcements offers additional weight savings of up to 25% compared to that using conventional orthogonal reinforcement.

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