COMPOSITE RISERS FOR OFFSHORE TECHNOLOGY

Yu. M. Tarnopol'skii[1], A. I. Beyle[1], and V. L. Kulakov[1]

Institute of Polymer Mechanics of Latvian University, Riga, LV-1006, Latvia

SUMMARY: Prospects of the application of advanced composites in the offshore technology of oil production are considered. Composite risers, especially drilling ones, are likely to be the first significant application of the advanced composites for deep-water offshore technology. The operating loads are studied and the attendant problems are formulated. A comparative analysis of the characteristics of metal, composite, and metal-composite deep-water risers is presented. A technique is developed for designing the multilayered risers taking into account the action of internal and external pressures, gravity, and axial tensile force created by tensioners, as well as the residual technological stresses due to the difference in coefficients of thermal expansion, physical-chemical shrinkage and force winding. The numerical estimations are given for a two-layered riser with inner metal layer from steel, titanium or aluminium alloys and composite layer from glass-fibre (GFRP) or carbon-fibre (CFRP) reinforced plastics formed by circumferential winding. It is shown that the technological stresses essentially affect the characteristics of the riser.

KEYWORDS: composite riser, residual stresses, force winding, buckling

INTRODUCTION

Offshore technology of oil and gas production, as well as mineral raw materials, not only on the continental shelf, but also at considerable depths of the global ocean is one of the most rapidly progressing branches of modern engineering. Extreme complexity of the problems originated leads to international efforts to their solution.

Design concepts were changed with the increasing of depth of oil production. Stationary platforms for the offshore applications supported by metal truss structures and standing at the sea-bottom, allow using the oil fields deposited at depths up to 300 m. At depths up to about 600 m, a mast-like structure in the form of a cylindrical or conical shell of large diameter, supported by a system of mooring lines and tendons is applied [1]. Considerable oil stores occur at depths below 1000 m. Therefore, the development of deep-water offshore technology based on a half-immersed floating platform connected with the sea-bottom by means of risers and held at the fixed position above the oil well with the help of a special system of the anchor mooring lines and tendons is of serious interest. This system comprises a set of vertical tension legs limiting the amplitude of heaves of the platform to the magnitude within 1 m, and a set of tilted tension members for preventing the horizontal and angular displacements of the platform. In the offshore oil terminology, this construction is called a

TLP-platform (Tension Leg Platform). Special tensioners ensure the vertical position of the riser [2].

High strength and stiffness of advanced composite materials in the direction of the reinforcing fibers in combination with a low specific weight, high corrosion resistance, and excellent fatigue characteristics are the reasons of their potential possibilities for the application in various structures of the offshore technology [3-5]. According to the most optimistic evaluation, the complex replacement of metal products by composite structures for only one TLP-platform would require the contemporary world annual output of carbon fibers. In former times, the needs of space-rocket and aeronautical engineering generated the modern composites as a new class of structural materials, technology of reinforcing fibers, binders and their processing into products, as well as large-series production of composites. At present, the process of demilitarisation has sharply reduced the industrial needs in composites and the production of composites requires new fields of application. The offshore business is one of intensified activity with rapid technological progress. It required 40 years of investigations and developments to go first 900 meters of the water depth, but next 900 meters increment occur over a less than five year span [4]. A number of international scientific conferences, beginning with the first Paris conference in 1994, as well as national USA conferences regularly held in Houston, have been dedicated to this problem. The actual advantages of the application of the composites in the offshore technology depend not only on their structural properties, but also, to a considerable extent, on the economic factors. However, it is necessary to note that for certain structural elements of the deep-water TLP-platforms, the application of composites may be the only solution. First and foremost, it concerns risers and anchor cables, for which the specific strength and stiffness of the material are the defining parameters.

The present report is dedicated to the analysis of problems arising in calculating and designing the deep-water metal-composite risers. The experts consider that the ultimate length of a steel riser should be within the range of 1000-1500 m. A metal-composite riser would make it possible that the oil production can be carried out in deep waters, since it retains the leakproofness of the structure owing to its inner metal layer. Besides, the riser weight and the expenses for tensioners can become much lower [3]. Moreover, the inner metal layer serves as non-removable technological mandrel. The efficiency of the metal-composite riser may be estimated using the principle of decomposition [6], according to which each element of the compound structure takes up generally one of the applied loads.

The present report describes a metal-composite riser of an two-layered design, uniform in length. The outer composite layer, formed by circumferential winding, provides basic resistance to internal and external pressures, while the inner metal layer bears the axial load. The loads acting on the riser essentially change along its length: the maximum pressures exist in the lower section of the riser, while the greatest axial tensile force acts in the upper part. High anisotropy of the physically mechanical properties of the composites as well as technological capabilities of controlling the heterogeneity of the characteristics by modifying the lay-up of reinforcing fibers allow one to optimize separately the structure of each section of the metal-composite riser. The technological solution of this problem is simplified owing to the engineering practice of manufacturing the risers by small-length sections. It should be emphasized that as a result of anisotropy of the physical-mechanical properties of composites and compound structure, there is a system of residual technological stresses and the attendant problems [7]. Another negative consequence of the anisotropy of the unidirectional composites is their low strength in transverse rapture and interlaminar shear.

LOADS ACTING ON THE RISER

The deep-water riser is a high-stressed structure subjected to a combination of concentrated and distributed (both the surface and the mass), static and dynamic loads, varying in the length. The concentrated forces and moments act mainly at places where the riser sections are joined with each other or with the floating platform and also at the place of the riser fixation to the sea-bottom. The distributed loads are caused by the weight of the riser and its interaction with the inside and outside fluids.

The riser is subjected to the following loads schematically shown in Fig. 1:

- internal, p_i, and external, p_o, pressures;
- force of gravity;
- top tension, N_z, of the riser by tensioners;
- reactive forces, N_x, R_x, R_z, and moments M_1, M_2, T;
- distributed transverse load, $q_x(v)$, due to the flow-past around the riser;
- distributed tangent load, q_z, stipulated by a current of a viscous fluid inside the riser;
- loads on the riser due to linear and angular displacements of the floating platform;
- buoyant force acting during the riser assembling, which also affects curvilinear sections of the riser while in use;
- random loads of various nature.

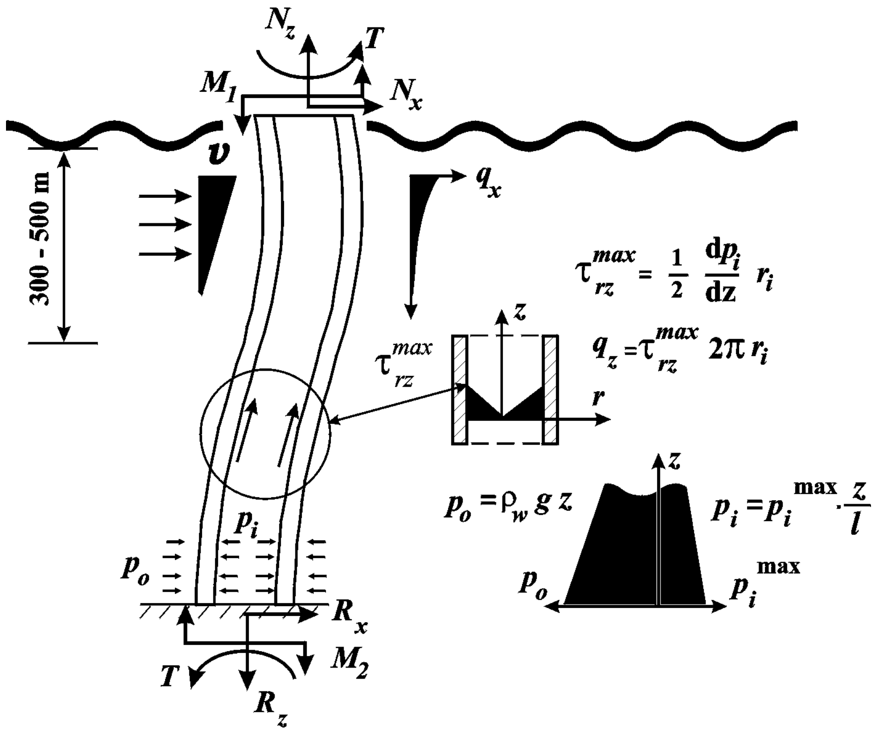

Figure.1. Scheme of loads acting on a riser.

The present study only deals with the first four greatest and constantly acting loads to be listed. This allows obtaining the preliminary estimations of riser parameters and the lower bound for safety factors necessary for the solution of the design optimization problem.

MODELS FOR RISER DESIGN

Stress-strain state of riser, for the chosen system of external loads, is calculated for two of its most stressed sections: near the junction with the floating platform (z = 0) and at the place of fixation to the sea-bottom ($z = l$). In the upper section, the riser is loaded mainly with the axial tensile force N_z assigned by the platform tensioner.

Required value of N_z is determined by the solution of buckling problem of riser. If riser is modelled as a thread, the required top tension equates to its total dead weight ($N_z^{\max} = M \cdot g$). If riser is modelled as a flexible rod, there are two possible variants. When riser length is less than the critical one being determined by only taking into account only force of gravity, riser is stable and top tension is not needed. In the opposite case, riser is able to resist only a part of compressive load and its vertical fixation requires an application of tensile axial force by tensioners. Nonlinearity of the buckling problems excludes a possibility to use principle superposition of the solutions, which had drawn separately for extended and compressed zones of riser. Analysis of riser buckling taking into account both compressive and tensile axial forces for four cases of fixation of the top end the rod and clamped its bottom end [8] gave the following results (Fig. 2).

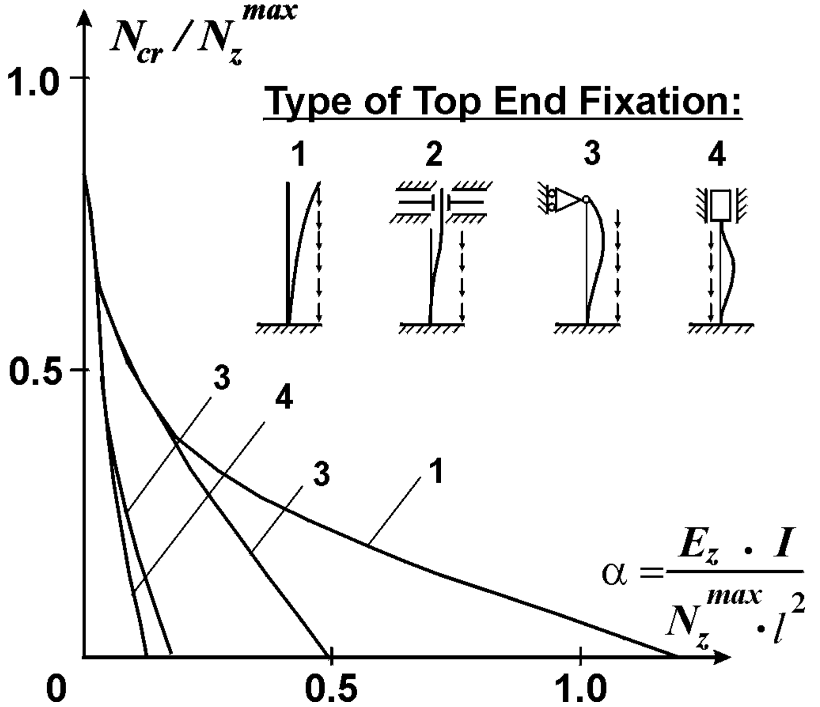

Figure. 2. Dependencies of reduced tensile force N_{cr} of the top end of riser on parameter α; E_z is modulus of elasticity, I is moment of inertia.

Though for riser operation, the magnitude of N_z is usually prescribed to be about 0.3 - 0.4 $N_z^{\max}$, the calculations of riser stress state were carried out below with its maximum value of $N_z^{\max}$. In the lower section, only the internal and external pressures are taken into consideration.

Tentative values of riser parameters firstly were calculated on the base of the membrane theory of shells. Application of the membrane theory of shells for the risers made of considerably anisotropic composites is restricted by rather small thicknesses of walls due to a high compliance of these materials in the direction perpendicular to the reinforcing fibers [9]. For the metal-composite risers, this approach is associated with much higher errors, since it takes no account of the essentially different radial strains of layers, both operational and technological.

A stress-strain state of the metal-composite riser was calculated by methods of the theory of thermoelasticity of an anisotropic layered body. The generalized Hooke's law describes the constitutive equation of a cylindrically orthotropic material along the principal axes of elastic symmetry. Thus, the solution of the problem is reduced to the solution of a system of linear algebraic equations with respect to the unknown contact pressures and axial strain for the given axial force, internal and external pressures, and gravity, with the account of thermal and free strains.

The temperature component of the residual stresses depends on anisotropy of the coefficients of linear expansion in composites and the difference between these coefficients in materials of compound structure. Different physical mechanical models for the account of these stresses are described elsewhere [7]. Thermoelastic model, which takes into account the cooling of cured products from the polymerisation temperature down to the operating temperature, was used. In thick-walled composite and compound structures, the level of these stresses may exceed the low composite strength in transversal fracture. Any attempt to reduce these stresses by decreasing the curing temperature for the binder at the expense of different compounding or physical effects (radiation curing, an electromagnetic field, etc.) may lead to quite an inverse effect owing to the increasing physical chemical shrinkage of the binder.

Another source of the residual technological stresses is the force winding of the composites or so-called prestressing created in the compound structure by radially expanding procedure. A linearly elastic statement of the problem allows one to substitute the total stresses (operational, as well as residual wound and thermal) in the adopted failure criterion of maximum stresses. The admissible stress level of the force winding is limited by several factors: the composite strength in tension along the reinforcing fibers, the compliance of the system of the wound layers and the inner metal layer serving as a technological mandrel, and the strength and stability of the mandrel. Basing on the experience of calculations and manufacture of wound structures, the maximum level of tangential stresses in the cured product, created by the force winding, in fractions of the composite strength in tension along the reinforcing fibers, was chosen 0.2. According to an approximate estimation of the stability of the metal pipe under external pressure of the composite circuits wound with tension, the minimum thickness of the metal layer is about 2 mm.

All calculations for the risers, uniform in length, were performed with the following selected values of parameters: inner radius of the riser a = 0.114 m; length of the riser l = 1500 m; internal pressure p_i = 34.5 MPa (chosen basing on the data of source bed pressure, which is counterbalanced by static pressure of liquid column with the density ρ = 1600 kg/m^3, containing oil, water and sand, and its losses by viscous friction); external pressure p_o = 14.75 MPa, equal to the pressure of sea water at a depth of 1500 m.

Load-carrying capacity of the riser was determined with the criterion of maximum stresses accounting for anisotropy of the composite strength. Normative factor n_{norm} in metals and composites was respectively chosen as 3.0 and 4.0, which adopted in the offshore technology.

RESULTS OF CALCULATIONS

Physical-mechanical properties of titanium and aluminium alloys, stainless steel and composites (GFRP and CFRP) used in the calculations are given in [10]. Approximate estimations of mass, wall thickness and safety factors of metal (steel, aluminium and titanium) and composite (GFRP and CFRP) risers obtained by membrane theory of shells showed that advanced composites with high specific tensile strength and stiffness allow to reduce considerably riser dead weight and as a consequence the top tension required [10]. Isotropic metal riser of a constant cross-section is impossible to design as a uniformly stressed structure. Therefore, safety factor accounting for the axial stress in the upper section exceeds the normative one and depends substantially upon the riser length. These preliminary results, disregarding the effect of some operating loads, still proved convincingly that structural possibilities of steel were really restricted by the depth of about 1000 m. Titanium riser is the best choice for metal ones. These preliminary results substantiate the expediency of application of a compound metal-composite riser for deep-water exploration. In this structure inner metal layer ensures its leakproofness and main resistance to axial load because of total weight of riser, while outer composite layer formed by circumferential winding provides main resistance to internal and external pressures.

Numerical calculations of two-layered metal-composite risers with the above-mentioned parameters l, a, p_i, p_o, (see section Models for riser design) were carried out for six combinations of structural materials, when inner metal layer was made from steel, titanium or aluminium alloys and outer composite layer was formed by circumferential winding of unidirectional GFRP or CFRP [10]. Calculations revealed significant influence of residual stresses due to thermal shrinkage on load carrying capacity of riser. Strong mismatching coefficients of linear thermal expansion, Poisson's ratios of composites and steel or aluminium alloys, as well as low tensile strength of unidirectional composites across reinforcing fibres are the main obstacles to use these materials in a single compound structure.

Physical-mechanical properties of titanium alloy and advanced composites show the best correlation each other. Dependencies of total mass M, thickness of composite layer h_2 and safety factor of composite layer n_θ with respect to circumferential stresses in the bottom cross-section of riser on thickness of titanium layer h_1 are shown in Figs. 3-5. Solid lines on the figures correspond to the calculations based on riser model as an anisotropic compound cylinder, while dash lines are calculations based on the membrane model of cylindrical shells. The calculations carried out in the elastic statement allow one to superpose the solutions obtained for independent action of operating loads and estimate their influence on the structure. Curve 1, 2 correspond to application internal and external pressures in the bottom cross-section and tensile force equaled total mass of riser in the top cross-section. Curves 3, 4 show extra influence of residual stresses of thermal shrinkage. Curve 5, 6 were computed with accounting for the operating pressures, residual thermal stresses and application of force winding which enables to reduce considerably effect of thermal shrinkage on load carrying capacity of compound riser and reduce its total mass (Fig. 3) and thickness of composite layer

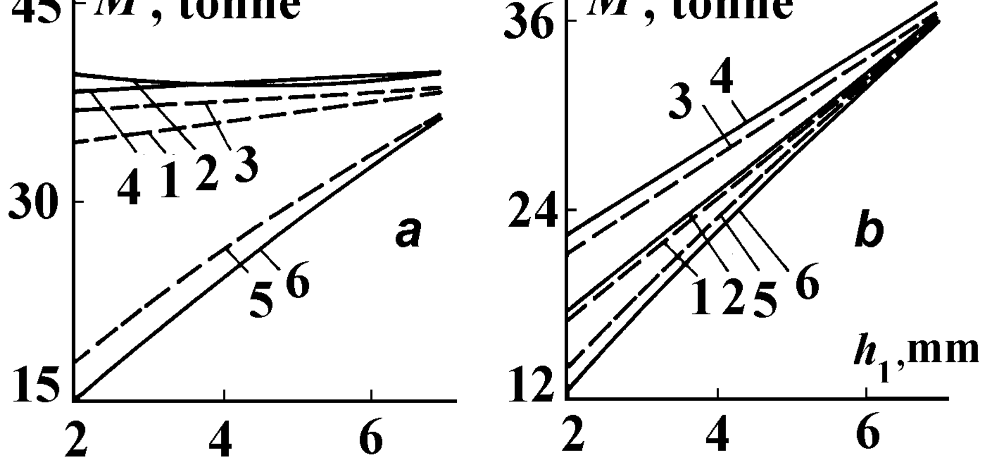

Figure. 3. Total mass of titanium-composite risers; a - GFRP; b - CFRP.

h_2 (Fig. 4). High anisotropy of the deformation and strength properties of the composites reduces substantially a conditional boundary between the thin-walled and thick-walled cylinders loaded by pressure, which separates them with respect of the relative thickness [9]. Of the same nature is the decrease in the deviation between the calculation results obtained by the membrane theory of shells and the solution of the linear thermoelastic axisymmetric problem of the theory of elasticity for an anisotropic body with the growing thickness of the composite layer.

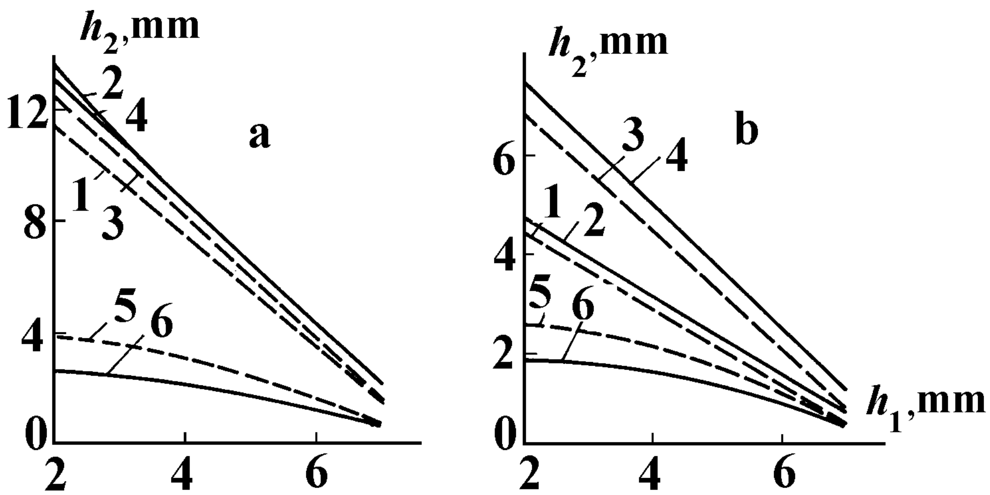

Figure 4. Thickness of composite layer in titanium-composite risers; a - GFRP; b - CFRP.

Owing to the force winding, it is possible to draw together the calculated safety factor of the composite layer with respect to the circumferential stresses, $n_\theta^{(2)}$, to its nominal value. The compatibility condition of the circumferential strains of the layers in the metal-composite riser without force winding leads to very high values of $n_\theta^{(2)}$, i.e., to an inefficient use of the composite.

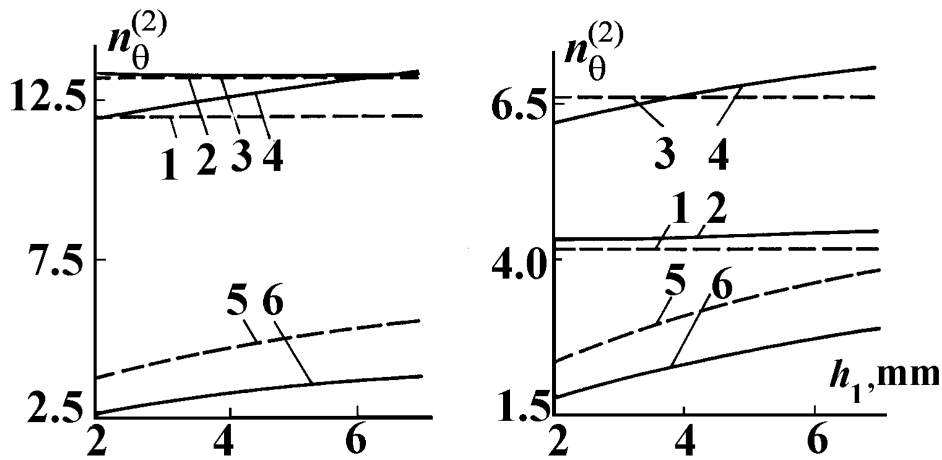

Figure 5. Safety factor of composite layer in titanium-composite risers; a - GFRP; b - CFRP

The calculations showed that combination of aluminium alloy with the considered composites and steel with CFRP did not ensure the required nominal safety factor in the metal layer without using the force winding. It seems that the control of the field of the technological stresses is, probably, a more efficient way for rational designing of the deep-water risers, than the application of the composite materials with extremely high elastic and strength characteristics.

However, the reduction of the riser mass by replacing most of the metal parts by the composite with circumferential reinforcement results in reducing the riser stiffness and effective strength in bending. Moreover, the replacement of the metal riser with a two-layered metal-composite one is accompanied by a decrease in the calculated safety factor concerning the axial stress in the upper section with the growth of its length and/or by a decrease in the thickness of the metal layer. Excessive decrease of the metal layer thickness with the extra circumferential winding by composite, which should ensure the specified load-carrying capacity of the lower riser section, may reduce the safety factor of the upper section so that it would become lower than the nominal. That is why, it seems reasonable to perform additional reinforcement by the composite material in the axial direction. This may be realized through other structural designs for the metal-composite riser: four-layers, two-layers with longitudinal-transversal or hybrid reinforcement. Effective design of so-complex structures as deep-water metal-composite risers supposes a necessity to solve of a series of engineering problems, some of which we summarized in Table 1.

Table 1. Models for Analysis of Mechanical Behaviour of Risers

Type of model	Loads accounting for	Problems to be solved
1. Extensible weighted thread	Dead weight, flow-past	Estimation of axial strength, effect of extensibility of riser axis on its deflection
2. Flexible rod in linear statement	Flow-past, reactive forces and moments	Calculation of riser deflection and stresses
3. Flexible rod in nonlinear statement	Dead weight, flow-past, top end tension, reactive forces and moments	Stresses, deflection, required top tension at longitudinal-transverse bending and buckling
4. Compound infinite anisotropic cylinder	Internal and external pressures, dead weight, residual stresses due to thermal shrinkage and force winding	Stress and strength analysis, selection of layer thicknesses and technological parameters
5. Compound semi-infinite cylinder	Effect of load distribution on riser ends	Stress concentration and length of boundary effect zone
6. Multi-layered cylindrical shell	Effect of asymmetric loading (flow-past, concentrated loads)	Stress and strength analysis
7. Cylindrical sections of different lay-ups on axial coordinate	Loads variation along axial coordinate	Selection of reinforcement scheme at different depths of sections
8. Cylindrical section with lay-up varying on wall thickness	Nonuniformity of stress fields on wall thickness	Optimization of reinforcement scheme of riser sections
9. Quasi-linear 3-D anisotropic elastic cylinder	Synergetic effect of different loads	Refined calculation of stresses

CONCLUSIONS

1. Application of composites enable to reduce considerably total mass of riser, required tension of its top end. Effectiveness of metal-composite riser rapidly and nonlinearly increases with depth of oil production.
2. Design and fabrication of metal-composite risers should take into account residual technological stresses. Rational selection of tension of force winding and other technological parameters allows one to increase considerably load-carrying capacity of risers.
3. Selection of required top tension of riser must be performed on the base of solution of buckling problem.

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