Composite riser design and development – A review

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ABSTRACT: There is accelerating interest in composite risers for deepwater applications. Composite risers offer much higher strength to weight ratios over metallic risers but there is less experience of their behavior in deepwater environments. A general review on current developments specific to composite risers highlighting the remaining challenges and the applications, design evolution, state-of-the-art modeling and experimental techniques is lacking. This paper provides such a review on fiber-reinforced polymer composite risers. The major issues for composite risers are addressed including the complicated combination of loads under harsh deep sea environment, the lack of long-term material degradation database for assessing the reliability of these riser systems and the need of effective numerical models to fully account for complex realistic loading configurations. The paper also highlights current gaps for design and application of composite risers in offshore technology and promising future research areas to help expand their utilization in deeper water.

1 INTRODUCTION

Production risers are the key devices of the floating offshore platforms. They are used to transfer the oil and gas from the wellheads at the seabed to the floaters on the surface. Different types of subsea production risers are used in the deepwater field including steel catenary risers, top tensioned risers, flexible risers or hybrid risers (Figure 1). While top tension risers and flexible risers are designed for shallow-water use, steel catenary risers are preferred for deepwater applications where large diameter pipes may be deployed. Traditional designs of production risers are based on steel or titanium, causing many challenges to the design extension, welding or installation of risers. Metallic risers become much heavier and require greater hang-off tension and resistances to high pressure and temperature variations with increasing water depth (Bai and Bai, 2010).

The applications of fiber reinforced polymer (FRP) composites in the offshore industry have been recently increasing, particularly in the areas of pipelines and production risers (Meniconi et al., 2001; Salama et al., 2002; Smith and Leveque, 2005; Suresh et al., 2004; Tamarelle and Sparks, 1987). Composite risers significantly help overcome the disadvantages of metallic risers in deep water since composite materials offer high stiffness to weight ratio, high tensile and fatigue strengths, low thermal conductivity and good corrosion resistance (Salama et al., 2002; Suresh et al., 2004). Composites also bring additional cost benefits as they can replace expensive stainless steel and titanium risers without compromising corrosion resistance and reliability (Fowler et al., 1998).

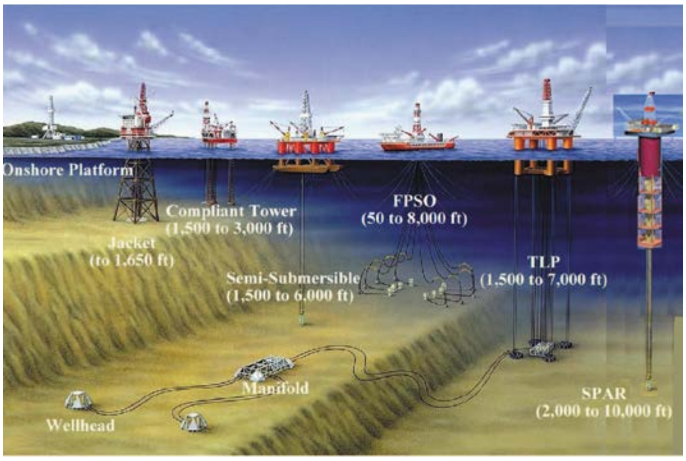

Figure 1. Different types of Platforms and Risers, Huang (Huang, 2012).

Production composite risers can be classified into two main types: bonded and un-bonded (Figure 2). Unbonded risers are flexible (American Petroleum Institute, 2008) where individual layers of the risers are able to move relative to each other. They have advantages in increased flexibility in field architecture, reduced maintenance and flexibility of installation (Hill et al., 2006). On the other hand, bonded composite risers often include a core of fiber-reinforced angle ply laminates bonded between a metallic/elastomeric inner liner and an outer liner made of thermoplastic or thermoset materials or metal alloys (Gibson, 2003). However, applications of FRP composite risers encounter many challenges. Some include the lack of full understanding of the mechanics and behavior of risers under deepwater environment, the lack of available S-N data for fatigue life prediction or the availability of full-scale testing of composite risers accounting for the scaling effects. The lack of knowledge imposes relatively high safety factors, from 15 to 50, for risers in the offshore as recommended by DNV (Det Norske Veritas, 2009).

a. b.

Figure 2. Two typical types of composite risers: (a) Bonded reinforced thermoplastic pipe (Gibson, 2003) and (b) Unbonded flexible pipe (Oil & Gas Journal, 1998)

There is current interest in exploring greater ocean depths. This requires a good understanding of the current riser designs and technologies and the associated mechanics and failures of risers under deep sea environment. Recently, there have been no comprehensive overviews of composite riser design and application. This paper is intended to provide a critical review of published literature on the design, mechanics and fatigue of FRP composite risers in the offshore technologies in the past decades. It is hoped that the review may highlight necessary requirements for deepwater composite risers and may pave the way for future research to increase the utilization of risers in ultra-deepwater.

2 ENVIRONMENTAL CONDITIONS AND LOADS FOR COMPOSITE RISERS

An important aspect in understanding the state-of-the-art relating to composite risers relates to the environment under which risers are subjected. Summerscales (Summerscales, 2014) describes riser environments as “being for long periods of time, often greater than 20 years, with a minimal amount of maintenance under high hydrostatic loads and high thermal gradients”. Guesnon et al. (Guesnon et al., 2002) expanded on these difficulties for ultra-deep water drilling riser designs showing that the factors also include water depth, mud weight, auxiliary line diameters and working pressures, sea states and current profiles and maximum rig offset.

Current calculations of the hydrodynamic loads typically use Morrison’s equation, outlined in Guesnon et al. (Guesnon et al., 2002). This approach is suitable for calculation of the hydrodynamic loads, incorporating the drag force due to the relative fluid velocity, and the inertia force due to the structural and wave acceleration, albeit that the viscous effects are not accounted for.

DNV (Det Norske Veritas, 2010) categorizes the loads on a riser as: pressure, functional, environmental and accidental loads. These different loads are created by the different currents and surface waves at sea, the pressures due to the change in depth and the interaction of the risers which are often deployed as a group.

Pressure loads are created by external hydrostatic pressure, internal fluid pressure, both static and dynamic, and the pressure caused by the depth at which the risers operate.

The functional loads include the applied top-tension of risers during the installation or construction, thermal loads due to thermal differences between the sea water and riser structure, or the weight of internal fluid, riser, casings, coatings or buoyancy modules.

Environmental loads are characterized by the wave, current, earthquake or floater motions.

Accidental loads are a separate group where the risk of the load occurring must be assessed with regards to a target failure probability. This ensures that the probability of these accidents occurring is less often than a predetermined value, often in the region of 10^{-3} to 10^{-5}.

Some estimated values for the loads and utilization factors of a riser with an internal diameter of 6 inches at high depth of 10,000 ft are given by Hill et al. (Hill et al., 2006). For more details, Patel and Seyed (Patel and Seyed, 1995) provide a review on the modeling and analysis techniques available to make a hydrodynamic assessment of flexible risers. This review gives a good basis for static and dynamic analysis, internal and external pressure effects and includes information on fluid flows.

3 MECHANICAL BEHAVIOR

3.1 *Experimental Investigation*

Carbon-fiber materials emerged as a potential offshore riser material over 20 years ago (Hatton, 2012). Salama et al. (Salama et al., 1998) reported a research program to develop testing and qualification procedures to validate the design and long-term performance of composite production risers for a tension leg platform in the Gulf of Mexico. The testing program developed in their research efforts aims at identifying the performance limitations, failure envelopes and the manufacturing requirements for the composite production riser.

Numerous previous experimental programs examine the mechanical performance of composite risers to ensure its applicability in the deep-water environment, as highlighted in Table 1. In review of past researches, the majority of the material characterization data come from the small-scale tests whose specimen's dimensions are much smaller than the actual components. A certain number of large-scale tests can be valuable aid in extrapolating data from small-scale to the full-scale tests and in helping identify unanticipated scale effects.

Recent programs on large scale composite testing are done by Ramirez and Engelhardt (Ramirez and Engelhardt, 2009) in which a collapse pressure test was performed on a full scale, carbon fiber-epoxy filament-wound tube to confirm the external pressure capacity of the composite pipe. The study indicates that the delamination in the wall of the composite pipe can cause a significant decrease in the external pressure resistance. Other programs on large scale design and manufacturing are reported by Thomas (Thomas, 2004). Drilling and production risers were both assessed statically and for fatigue against experimental data to derive a performance database. The optimal solutions were derived based on satisfaction of design, manufacturing and inspection criteria. Moreover, Salama et al. (Salama et al., 2002) described the first offshore field installation for a composite riser joint in the Heidrun tension-leg-platform in the Norwegian North Sea. The qualification program includes mechanical and fatigue testing on full-diameter riser joints. Lindsey and Masudi (Lindsey and Masudi, 1999) reported an experimental study on the graphite-epoxy composite under cyclic tension over a temperature ranging from 24℃ to 75℃ in a seawater environment. Their experimental work compares the fatigue performance for two different fiber orientations in offshore drilling risers, while contributing to the fatigue database required in developing the S-N curve for fatigue life estimations.

The last few decades have observed significant experimental development in investigating the mechanical performance of composite risers. Such experimental work mainly focuses on the ultimate behavior of the composite tubes subjected to tension, bending, and burst pressure under different environmental conditions. These developments lead to the subsequent development of guidelines on the qualification tests for composite risers in the design codes. However, full-scale fatigue tests for the composite pipes are still insufficient for the development of a specific S-N curve to provide quantitative estimation of the fatigue life of composite pipes.

Table 1. Experimental programs on composite risers

Reference	**Type of specimens**	**Highlight of the study**
Sparks and Odru (Sparks et al., 1998)	Production riser for tension-leg platform	Mechanical properties for the composite risers used for concrete tension leg platform.
Gibson (Gibson, 2003)	Fiber reinforced composite coupons and pipes	A 13-year research project for the general use of composite materials in offshore applications, including fire, impact, blast and durability.
Ramirez and Engelhardt (Ramirez and Engelhardt, 2009)	Full-scale composite tube	Collapse pressure test
Rodriguez and Ochoa (Rodriguez and Ochoa, 2004)	Carbon-fiber epoxy tube and glass-fiber epoxy tube	Four-point bend flexural tests
Lindsey and Masudi (Lindsey and Masudi, 1999)	Graphite-epoxy composite	Cyclic tension from 24^0C to 75^0C in a seawater environment
Alexander and Ochoa (Alexander and Ochoa, 2010)	Carbon-fiber composite repaired steel riser	Full scale experimental test covering burst pressure test, tension test and four-point bend test.

3.2 *Numerical Analysis*

There are various studies in literature covering mechanics and nonlinear failure analyses of composite risers due to tension, compressive, bending, torsions and their combined loading in the presence of internal fluid pressure and hydrostatic pressure of seawater. Corona et al. (Corona and Rodrigues, 1995) analyzed the bending response of long and thin-walled cross-ply composite cylinders including three phases: pre-buckling response, material failure and shell-type bifurcation buckling. The bending moment-curvature behavior of the linear elastic composite tube in Corona (Corona and Rodrigues, 1995) was observed to be nonlinear due to the progressive ovalization of the cross-section, which correlates well with the reports by Brazier (Brazier, 1927) and Reissner and Weinitschke (Reissner and Weinitschke, 1962). Corona (Corona and Rodrigues, 1995) proved that a cylinder with all 0^0 fibers can obtain a high bending stiffness but buckling was likely to occur much earlier due to increased ovalization effects from the lack of 90^0 fibers. Seide and Weingarten (Seide and Weingarten, 1961) considered the buckling failure in its bending mode which occurs when maximum compressive stress in the structure reaches the critical stress under pure compression and where the pre-buckling response was found to contribute to the bifurcation load through ovalization (Axelrad, 1965, 1987). Cheng and Ugural (Cheng and Ugural, 1968) concluded that higher maximum bucking load of the cylinder may be attained if the fibers in the inner and outer layers are oriented circumferentially in an analysis without consideration of the nonlinear pre-buckling.

Meniconi et al. (Meniconi et al., 2001) investigated the feasibility of hybrid carbon and glass epoxy composite risers for a tension leg platform. The riser consisted of carbon fiber core layers wound at $\pm 20^0$ sandwiched between inner and outer layers of glass fibers. Hydrodynamic finite elements were used to estimate the axial forces and bending moments of the riser taking into account different environmental loading conditions. For delamination analysis of the taper joints, an initial crack was assumed at the tip of a resin pocket and a virtual crack closure technique was applied by Rybicki and Kanninen (Rybicki and Kanninen, 1977) to calculate strain energy release rates. The results show that composite risers which satisfy design and strength requirements can weigh half as much as an equivalent steel riser.

Rodriguez and Ochoa (Rodriguez and Ochoa, 2004) presented experimental and computational analysis of the failure of spoolable composite tube under bending and investigated the effects of material systems, layup stacking and geometry. It was found that the reduction in shear stiffness may dominate the nonlinear bending responses of the tubes. Furthermore, it is shown that undamaged tubes of glass can be cooled on a smaller spool than carbon.

Theotokoglou (Theotokoglou, 2006) described delamination buckling of thick composite tubes subjected to external pressure. Although cylinder tubes may fail in multiple ways under combined axial-pressure loadings (Marinucci and de Andrade, 2006; Tafreshi, 2004; Wiggenraad et al., 1996), delamination-type failure was commonly encountered in thick composite cylinders (Bai et al., 1997; Rasheed and Tassoulas, 2001; Zhao et al., 2000). Potential delamination of the cylinder such as annular delamination (Kachanov, 1988), strip-type delamination (Timoshenko and Gere, 1961) and buckling of the delamination regions were numerically investigated by Theotokoglou (Theotokoglou, 2006). In addition, Vedvik et al. (Vedvik and Gustafson, 2008) analyzed filament wound thick composite pipes with metal liners subjected to progressive matrix cracking and plastic flow under axial loading. This damage model was able to simultaneously predict the progressive transverse cracking of angle ply laminates and plastic yielding of the metal liner. Andersen (Andersen, 1996) coupled minimum potential energy approach based on the displacement field with the average maximum stress, average maximum strain, maximum point stress and maximum point strain criteria to model the progressive damage of $[\pm 55^0]$ and $[\pm 45^0]$ laminates. Mendelson (Mendelson, 1968) employed the successive elastic solution with von Mises yield criterion for plasticity modeling the liner. It was found that when both methods were applied in parallel the equilibrium conditions and two convergence criteria must be fulfilled for every load increment. Pina et al. (Pina et al., 2011) and Vieira et al. (Vieira et al., 2008) performed a global analysis of bonded composite risers using an analytical catenary solver and Abouhamze and Shakeri (Abouhamze and Shakeri, 2007), Larson and Hanson (Larsen and Hanson, 1999) and Lima et al. (Leite Pires de Lima et al., 2005) used static finite analyses to compute the axial force of the riser considering the riser to be inextensible under distributed vertical load. Ramos and Pesce (Ramos and Pesce, 2004) presented an analytical model to predict the behavior of flexible risers under a combination of loads, bending, twisting, tension and internal and external pressure. This method gave a reasonable agreement with experimental results but it was proposed that modeling slip between layers, using friction, would allow a coupling between bending and axisymmetric loads.

Recently, Sun et al. (Sun et al., 2013) proposed a homogenization approach for stress analysis of production risers where multilayers of composite can be considered as one homogenized orthotropic layer with blended elastic properties. The predicted stress/strain distribution results for different layups and radii by the homogenized model agree favorably well with other solutions in literature such as those developed by Xia et al. (Xia et al., 2001) or Tarn and Wang (Tarn and Wang, 2001). This method may be accurate for balanced angle-ply composite laminates but the accuracy must be investigated for composite cylinders with unbalanced angle plies.

Table 2 highlights numerical methods for composite risers carried out in the past decades. Many researches on general composite tubes have been covered in literature addressing the buckling responses and possible delamination-type failures in composites under bending, compression or combined axial-bending loadings by failure criteria and numerical methods. However, particular researches on composite risers considering realistic deepwater conditions are still limited. This requires full consideration of complex loading combinations in harsh environmental conditions. Moreover, not only should the analysis of the composite body be performed by effective modeling methods but also damages at mechanical joints, metal composite interfaces and end fitting terminations must also be carefully evaluated.

Table 2. Numerical methods for composite risers

Reference	Focused Areas	Methods
Corona et al. (Corona and Rodrigues, 1995)	Bending response of long and thin-walled cross-ply composite cylinders	Non-linear analysis with material failure criterion and constitutive modeling
Brazier (Brazier, 1927)	Bending of thin cylindrical shells	Non-linear bending analysis
Reissner and Weinitschke (Reissner and Weinitschke, 1962)	Bending of circular cylindrical tubes	Non-linear bending analysis
Sei and Weingarten (Seide and Weingarten, 1961)	Buckling of cylindrical shells under pure bending	Non-linear pre-buckling and buckling analyses with failure criteria
Axelrad (Axelrad, 1965, 1987)	Theory and analysis of flexible pipe in consideration of pre-critical deformation	Buckling analysis and ovalization effects
Cheng and Ugural (Cheng and Ugural, 1968)	Buckling of composite shells under pure bending	Buckling analysis and determination of buckling loads
Meniconi et al. (Meniconi et al., 2001)	Design of composite riser stress joints	Progressive failure analysis of composite taper joints with hydrodynamic finite elements
Rodriguez and Ochoa (Rodriguez and Ochoa, 2004)	Flexural response of spoolable composite tubular	Experimental and computational analysis of spoolable tube under bending by 2D shell elements and a material failure model
Theotokoglou (Theotokoglou, 2006)	Delamination buckling of thick composite tubes	Annual and strip-type delamination induced buckling are investigated by 2D FE models
Vedvik et al. (Vedvik and Gustafson, 2008)	Analysis of thick walled composite pipe with metal liner	Damage models developed to predict progressive cracking of angle ply laminates and plastic yielding of the metal liner
Andersen (Andersen, 1996)	Analysis of transverse cracking in composite structures	Minimum potential energy approach with multiple failure criteria are employed to model the progressive damage in composite laminates
Sun et al. (Sun et al., 2013)	Stress analysis of multi-layered composite offshore production risers	A homogenization approach for stress analysis is proposed and its elastic constants are determined by force-displacement equivalence method

4 FATIGUE CHARACTERIZATION AND BEHAVIOR

Much research has attempted to estimate the fatigue life of composite risers using different fundamental approaches derived originally for pipes made of other materials, as summarized in Table 3. The general fatigue methods in the literature could be classified into two groups: cumulative fatigue damage (CFD) and fatigue crack propagation (FCP). Hao et al. (Hao et al., 2000) proposed CFD models by finite element and mesh free method to account for the influences of microscopic parameters on macroscopic stress, strain and energy density. Roessle and Fatemi (Roessle and Fatemi, 2000) and Lynn and DuQuesnay (Lynn and DuQuesnay, 2002) presented the strain-based and energy-based methods for fatigue predictions of marine structures. Cui et al. (Cui et al., 2011) presented different CFD approaches based on stresses, strains, energy terms and continuum damage mechanics. The stress-based approach is the most popular method for fatigue life prediction due to its simplicity. Most of the stress-based fatigue approaches were based on the assumption that load sequence effects are neglected and require the prescription of fatigue loadings, the availability of existing S-N curve database and the determination of stress concentration factor. The fatigue life of a structure under multi-axial loading has been estimated by methods based on principal stress ranges, effective stresses or stress states at different crack planes (Li et al., 2001; Sonsino and Kueppers, 2001; Van Dang et al., 2001; Yousefi et al., 2001). Different from the CFD method, the FCP approach is based on fracture mechanics and can take into account load sequence effects. There have been studies adopting the FCP approach for fatigue life assessment (Cui, 2002; Miller, 1999; Newman Jr, 1998).

Fatigue of composites may start from the microscopic scale which involves microscopic failure in constituent fiber, matrix or fiber/matrix interface to the macroscopic scale that considers failure at structural level (Muc, 2000); (Van Paepegem et al., 2001); (Chen et al., 2002). Damage was found to initially grow in small increments and remain at a constant growth rate thereafter before they accelerated in the last stage. Lian and Yao (Lian and Yao, 2010) recently estimated the fatigue damage evolution and fatigue life of composite laminates under cyclic loading to account for stiffness degradation in longitudinal, transverse and shear directions with limited data from experiments. Both stress analysis and fatigue analysis were carried out and either discount strengths due to failure or discount properties due to fatigue were calculated at each load increment. This study provides a simplified framework for fatigue damage prediction but more experiments and numerical analyses are required to understand the fatigue behavior of composite laminates.

Despite the above research on the fatigue behavior of composites at the material level, the investigation on the fatigue performance of FRP riser product remains scant. Ochoa and Salama (Ochoa and Salama, 2005) highlighted the lack of experimental database for long-term damage mechanisms required by the accurate fatigue life prediction methods remains one of the basic technical barriers for wide industrial applications. A reliable S-N curve has not yet evolved for composite risers. The lack of experimental efforts on the composite risers leads to large factors of safety in the offshore design recommendations (Det Norske Veritas, 2009). The development of a comprehensive fatigue design procedure requires extensive experimental data for composite riser prototypes fabricated following the exact procedure as that for commercial products. Some fatigue tests have been performed on composite riser specimens (Cederberg, 2011; Huybrechts, 2002); (Lindsey and Masudi, 2002); Kim (Kim, 2007). However, most of the methods were developed from cyclic tests of small-scale riser specimens instead of the full-length riser specimens and hence their scaling effects have not been fully addressed.

In summary, the experimental researches available in the literature have not provided sufficient data necessary to develop an explicit S-N curve for composite risers. Extensive industrial applications of composite risers require inevitably specific S-N curves developed for these composite risers corresponding to different dominant failure mechanisms.

Table 3 Fatigue studies on composite risers

Reference	**Type of specimens**	**Type of study**	**Method used**
Cederberg (Cederberg, 2011)	Steel-reinforced steel drilling riser	Fatigue life estimation	Strain-life model
Kim (Kim, 2007)	Composite risers	Fatigue life estimation	Semi-log S-N approach; Power-law S-N approach
Echtermeyer et al. (Echtermeyer et al., 2002)	Composite risers	Fatigue life estimation	S-N approach
Huybrechts (Huybrechts, 2002)	Composite reinforced polymer riser	Fatigue life estimation	S-N approach
Lindsey and Masudi (Lindsey and Masudi, 2002)	Carbon-fiber and e-glass fiber composites	Experimental test	Empirical fatigue curve

5 CONCLUSION

With the growing importance and prevalence of deep-water exploitation there is an increasing benefit in deploying composite risers. Whilst relatively few examples of composite risers currently exist, it is hoped that research will provide a platform for an expanded utilization of these materials. There is currently no state of the art review focusing on the importance, range of applications and associated mechanics of composite materials in risers, this article aims to provide such a review. The review shows that the predicted benefits of using composite materials for risers are large with potential weight savings, decreased costs and increased structural and fatigue strengths. Reliable experimental and numerical approaches have to be adopted to effectively predict the mechanical response of composite risers and account for complex environmental loads in deep-water applications. For fatigue, it is seen that sufficient fatigue stress-life (S-N) data for composite risers are not readily established in the literature leading to the current large fatigue safety factors, 15 to 50. Utilization of reliability analysis within the field will also help to reduce these safety factors as has been done for many other applications.

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