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State-of-the-art review of composite marine risers for floating and fixed platforms in deep seas

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ABSTRACT

The need for the utilisation of marine risers in deep seas has increased in recent years and this is due to increased drilling explorations with the shift in trend from shallower to deep and deeper waters. Also, there have been increased applications in sea-crossing infrastructure resulting in the need for longer risers, leading to a significant weight increase of marine risers used. Composite materials can thus be utilised in marine riser engineering to provide lightweight, fatigue-resistant, corrosion-resistant, low-bending stiffness and high-strength characteristics. In this paper, the history and potential of composite marine risers, including the first successful deployment of a composite riser joint offshore on the Heidrun Platform in 1995, are reviewed. The paper also discusses the advances achieved on composite marine risers for deep waters and presents some recommendations on their use, in light of their current significance and growth.

1. Introduction

There is a growing demand and commercial interest in utilising composites or composite materials as alternatives in several engineering designs (Amaechi et al., 2019; Elchalakani et al., 2023; Guz et al., 2015; Ye, 2003). Such designs include industrial, domestic, aviation and marine applications (see Reda et al., 2021a, 2021b; Amaechi et al., 2021; Bai and Bai, 2005, 2010). Offshore composites are not as popular as they ought to be given the size of the offshore industry. However, various technologies on Subsea Umbilicals, Risers and Flowlines (SURF) have been applied in the industry, particularly composite marine risers, which have been studied for almost a quarter-century and greatly benefitted the offshore industry and SURF markets (Saleh 2015; Brown 2017; C.V. Amaechi 2022). Marine risers, which are a class of subsea risers, have unique applications and benefits in the offshore sector. The use of these riser pipelines is essential for drilling, extracting and transporting oil products from oil wells. Thus, they must be designed specifically with consideration to safety and corrosion resistance and deep-water environments, amongst other things. Multi-layered conduit marine risers and hoses are developed for transferring fluid on hydrocarbon platforms. This implies that the water depth, the maximum static offsets and the heave motions imposed by the floater are important factors to select the most suitable geometry of the riser used. Fig. 1 shows a typical offshore field showing the marine risers.

Three common types of marine risers can be used in riser applications, mainly non-bonded flexible pipes, thermoplastic composite pipes and hybrid flexible pipes. Non-bonded flexible pipe risers have been applied in the offshore oil and gas industry for many decades. They have been used for connecting seabed flowlines to floating production systems, and for static seabed flowlines. In some cases, they have proved to be more economic than rigid pipes in harsh environments or when they are desired to recover the flowlines for reuse after a short field life. The design of the traditional flexible pipe riser (as shown in Fig. 2) consists of a stainless-steel internal carcass for collapse resistance, an extruded polymer fluid barrier, a carbon steel interlocked hoop strength layer, a helically wound carbon steel tensile armour for axial strength and an extruded watertight external sheath. For dynamic applications, the extruded polymer or tape polymer anti-wear layers are applied between

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the adjacent steel armour layers. For extremely high-pressure applications, an additional layer of rectangular-shaped helical reinforcement over the interlocked hoop strength layer, or a second set of tensile armour layers, may be applied. The structure of the traditional flexible pipe risers is inherently thermal-resistant and corrosion-resistant; thermal insulation layer(s) can be added under the external sheath to provide additional thermal resistance. The traditional flexible pipe risers have the advantage of accommodating larger platform motions than rigid risers. They are suitable, even in high-sea states, for use with semi-submersibles and turret-moored ships when rigid risers would be unsuitable. Despite the inherent advantages of traditional flexible pipe risers, they have technical and economic limitations. It is well recognised by the industry that the use of flexible risers from the floater to the sea floor in deepwater needs an exceptional design to withstand the extreme external hydrostatic pressure and large top tension.

Thermoplastic Composite Pipe (TCP) risers are alternative pipe risers that, unlike traditional flexible pipe risers, have a solid wall construction constituted of a single polymer material reinforced with embedded (melt-fused) fibre reinforcements. The solid wall consists of four components: a thermoplastic pressure barrier bonding layer, a laminate layer and an outer layer, as illustrated in Fig. 3. All layers are of the same thermoplastic polymer and fused during the production process to form a solid, fully bonded TCP riser. This process secures the strongest interface possible between the layers. TCP risers have a simple design with many advantages such as excellent corrosion resistance, ease of installation due to their lightweight and improved fatigue life. Table 1 highlights a typical example of a TCP riser with the material selection. Example of existing industry applications are seen in Strohm's TCP risers. The light weight of the TCP risers assists to reduce the loads on the host platform and results in larger riser motions as well as lateral deflections. The downside of the TCP risers is the challenges faced by the designer to find a suitable configuration. Another downside of the TCP risers is the susceptibility to failure under bending loading due to the glass/carbon fibres disengaging from the polymer matrix.

In addition to traditional non-bonded flexible pipe and TCP risers, some manufacturers started a new design called Hybrid Flexible Pipe risers. In this new design, layers of the flexibles are replaced with composite materials to enhance the durability of the pipe and increase certain technical characteristics. For instance, the tensile armour wires are replaced with strips made of rectangular carbon fibre-based composite. As indicated by Hanonge et al. (2013), this new hybrid design had many advantages such as the composite wires can bend more easily than carbon steel wires, resulting in reduced bending stiffness for small curvature. In addition, the hybrid design is around 30–60% lighter than the traditional design.

Offshore composite materials have been used previously in secondary structures that cannot bear loads such as guard rails. According to previous studies, the development of composite risers has benefitted from the advancements in other fibre composites, including composite material lamination and tubular designs (C.V. Amaechi et al., 2019; Gillet 2018). Comparative tests of composite risers against steel risers have revealed that composite risers render numerous benefits, particularly low weight and cost savings (Gillet 2018; C.V. Amaechi et al., 2022; Reda et al., 2018). Historical timelines on the first successful deployment of a composite riser joint were offshore on the Heidrun Platform circa 1995, which showed that the true potential of composite risers can be adapted and utilised (Salama et al., 2002). Other components of marine risers include the metal-composite interface (MCI), end-fitting and filament-winding composite fibres. In one full-scale application by Shell for Top Tensioned Riser, the riser was compromised of Composite Production Risers (CPR)'s tensioner accumulation bottles made of composites, used in the Gulf of Mexico (GoM) to reduce deck loads on the Mars Oil Platform. This application showed that better results can be achieved from reduced CPR pipe weight for the same strength performance and thus the use of more CPR pipe adaptable configurations can be recommended. This finding led to the use of compliant configurations such as Single Leg Hybrid Riser (SLHR) concepts for CPR riser deployment (Saleh H. 2015; Brown T. 2017), and Multibore Hybrid Riser (MHR) configurations for CPRs and spoolable TCPs (Cheldi et al., 2019). It is worth mentioning that the original SLHR were made of steel pipes, however, the manufacturer company also tried to develop a similar riser configuration using the traditional flexible pipe. Around 2014, there were reported pre-commissioning projects in pre-salt offshore Brazil using 3-inch bore fully composite pipes under a water depth of over 2,100 m (6,890 ft). This project led to an upscaling in the use of composite pipes and TCPs. Examples of the use of composite pipes and TCPs can be seen in recent composite risers applied recently in Brazil by Magma and OCYAN (see Fig. 4) and in Netherlands and UK by Airborne Oil & Gas, and Magma Global (Hatton et al., 2013; Onna et al., 2014; Barbaso 2018).

Considering the significant growth in the utilisation of marine composites, there is a need to review composite riser developments. Also, different studies have reported some common failure modes on composite risers (Reda et al., 2021a; Drumond et al., 2018; Marinho et al., 2007), therefore, there is a need to further investigate such a technology and its findings. In this paper, a comprehensive review of composite risers for deep water on floating and fixed platforms is conducted. The paper gives an overview of the utilisation of composite risers, including the recent progress and advances, development clarifications, prospective applications, design configurations, and benefits and challenges.

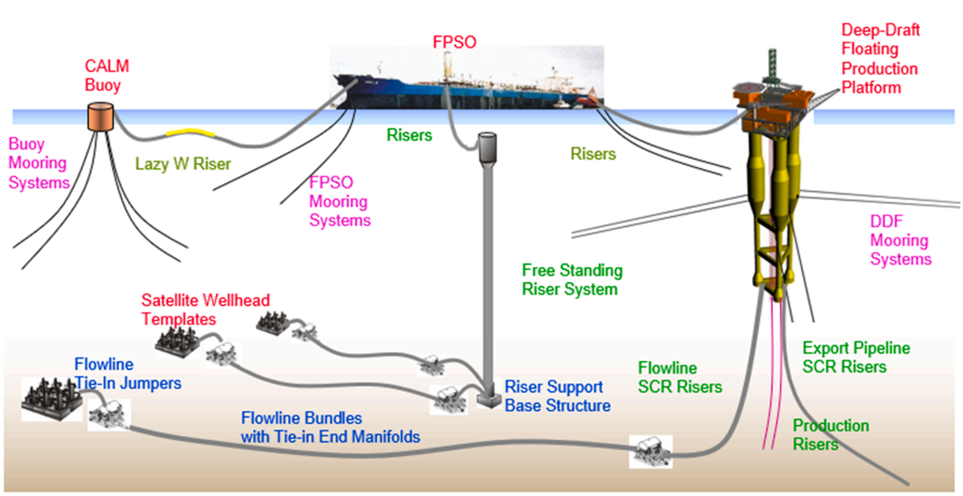


Fig. 1. Typical offshore field showing marine risers, flowlines and subsea modules.

2. Historical review and developments

In the 1980s, Institut Francais du Petrole (IFP) and Aerospatiale were the first to attempt the design and development of composite risers (Ochoa and Salama, 2005; Sparks et al., 1992). Several patents made about composite risers were issued, including composition material tubes that were considerably unkind to length variations under the impact of internal pressure (Tamarelle and Sparks 1987; Sparks et al., 1988). Later, in 1985, IFP and Aerospatiale worked on developing a larger diameter composite tube (2.94 m) for injection and production risers, both for deep-water. The tube was built with a burst pressure of 105 MPa, an ultimate tension of 450 tonnes and a maximum temperature of 110 °C, and the results were used to analyse the performance of the used and damaged tubes, along with non-destructive test procedures. In the 1990s, IFP established a production technique and invented a composite material tube with a fibrous thermoplastic coating. The tube was endowed with at least one inner coating of fibrous composite material impregnated with a thermoplastic binder, which was directly adjacent to the tubular portion formed by the structural portion with the thermosetting binder. The tube was made of a structural component of composite fibres encompassed with thermosetting matrixes acting as a binder and obtained by filament winding. Andersen (1994) presented a composite riser ideal for drilling in inclement weather and for production risers that would use composite materials such as graphite or E-glass fibres with an epoxy matrix. Later, the NIST Advanced Technology Programs achieved potential advancements in composite risers research. More composites and composite tube experiments have been conducted since 2000. At least one sealing sheath comprised of a low-permeability polymer material was used to create a patented multilayer composite tube composed of composite material and reinforcing fibres inserted in a polymer matrix (Odru et al., 2002). Another innovative effort was made on a workover riser system for 3000 m water depth using a composite riser joint that was more cost-effective and adept at becoming implemented using an autonomous control system without an umbilical. The design was made using a 0.445 m ID marine riser with a working pressure of 345 bar (5,000 psi) and a temperature range of 2–120 °C (Moreira et al., 2003).

Although the design of marine risers began in the early 1900s, a shift occurred due to the introduction of the Graphical User Interface (GUI) and the advent of the millennium computers in the early 2000s, and as such, the numerical analysis in the design of composite risers commenced. This led to advances in both the composite industry and the offshore industry on composite risers, composite flowlines and composite pipes. In November 2012, Airborne Oil & Gas delivered a TCP downline and reeling system to Saipem SA. It was successfully installed in 2014 in Saipem SA's field – Guara and Lula, Brazil, with a water depth of 2,140 m. The project involved 4 pipeline pre-commissioning campaigns with 45 deployments based on its operation in deep-water Brazil (Kanter et al. 2015). In September 2016, the world's first permanent TCP and TCP hydrocarbon flowlines were installed in Chevron's HPHT (High-Pressure, High-Temperature) Alder field of 152 m water depth in the North Sea. Chevron and Airborne Oil & Gas successfully installed both a TCP flowline and a TCP jumper, for permanent methanol injection. Alder field is a gas condensate field developed by Chevron Upstream Europe (CUE) in 2014, with the requirement for high pressure (12,500 psi), easy ROV manipulation, flexibility and lightweight. It has a single subsea well with a TCP jumper that connects the manifold to the X-mas tree. The TCP jumper spool operates at a constant pressure of 622 bar (Spruijt 2018). Later in December 2017, Petronas and Airborne Oil & Gas successfully installed a TCP flowline pilot of 15.24 cm (6-inch) diameter on a platform off the coast of Sarawak, Malaysia, for a full well bore service of hydrocarbons. This TCP replaced the metallic pipes that had issues with corrosion, after a 5-year qualification (Jak 2018; Spruijt 2018). According to Jak (2018), Technology Readiness Level 6 was awarded to Airborne Oil & Gas by Petronas Malaysia after monitoring the successful installation of the TCP flowline in Sarawak. Qualification experience according to DNVGL RP-F119 (DNVGL 2015) reported that the TCP flowlines were successful (Spruijt 2018; Kanter et al. 2015; Onna et al., 2014).

The above historical review is necessary to present the developments made and challenges encountered in the deployment of composite risers in deep water areas. Deepwater operations, in general, necessitate the use of large machinery (C.V. Amaechi et al., 2022). Thus, the use of composite materials in deep water operations, such as composite risers, provides numerous advantages. Compared to traditional steel risers or

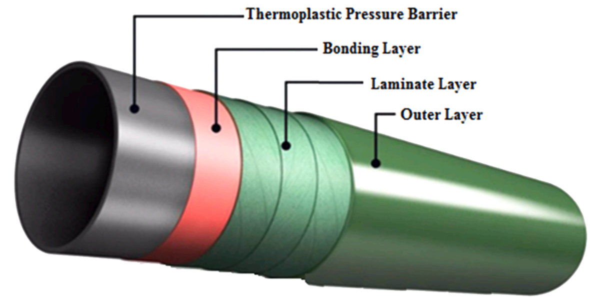


Fig. 3. Typical example of TCP riser showing its different layers.

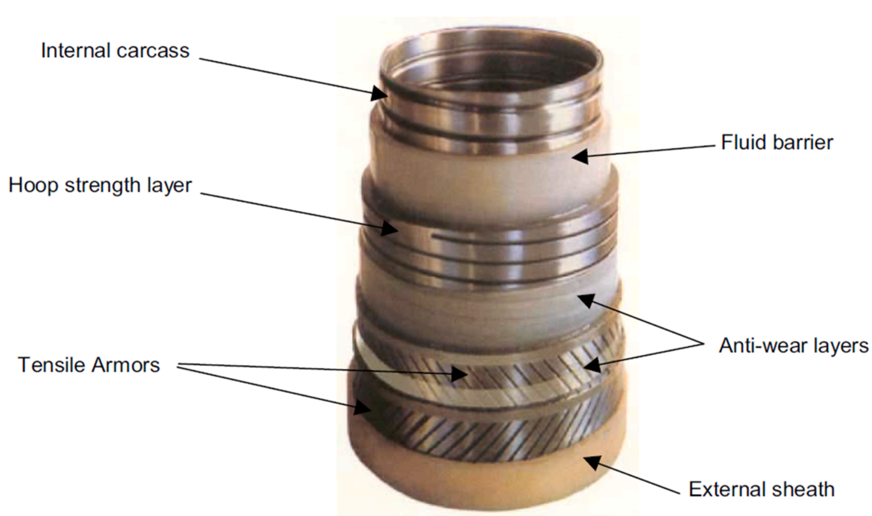


Fig. 2. Configuration of a typical example of a non-bonded traditional flexible pipe riser.

Table 1
Typical example of a TCP riser with the material selection.

TCP Material	Fibre	Polymer	Type of service	Applications	Max. operating temperature
E-glass/ Polypropylene	Glass	PE	Acids, methanol, Nitrogen & Water	TCP riser, TCP flowline, TCP jumper and TCP jumper spool	60 °C (140°F)
E-glass/Polyethylene	Glass	PE	Acids, Hydrocarbon, Methanol, Water	TCP riser, TCP flowline, TCP jumper and TCP jumper spool	60 °C (140°F)
Carbon/HDPE	Carbon	HDPE	Hydrocarbon	TCP riser, TCP flowline	60 °C (140°F)
Carbon/PVDF	Carbon	PVDF	Hydrocarbon	TCP riser, TCP downline	130 °C (266°F)
Carbon/PA12	Carbon	PA12	Sea water & Hydrocarbon	TCP riser, TCP flowline, TCP jumper and TCP jumper spool	80 °C (176°F)
Carbon/PA11	Carbon	PA11	Sea water & Hydrocarbon	TCP riser, TCP flowline	80 °C (176°F)

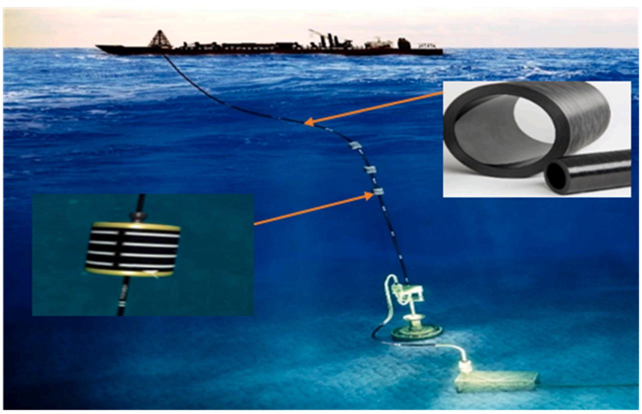


Fig. 4. A typical composite riser configured using Magma's M-pipes solutions as a lightweight and cost-saving riser (Adapted with Permission; Courtesy: Technip's Magma Global).

other marine risers, composite risers have a distinct advantage in terms of weight. For a long time, subsea operations have been drifting towards deep seas and this has been made feasible - thanks to a slew of new advances in the sector (Penati et al., 2015). Existing platforms can be modified by deploying composite risers, according to a previous study by NIST-ATP (NIST, 2005), which displayed platform projections with composite risers on redeployed platforms for composite riser applications. In addition, composite risers are less expensive due to the advantages of less weight per metre of production. Other advantages include increased protection from seawater temperature, the ability to reach deeper depths, low installation cost corrosion resistance, low operating cost (no requirements for chemical inhibitor) and capacity to reach higher sea depths. The main advantage of composite risers is the ability to recover, and relay fluid products and adapt the conduit materials used in new projects. The used risers are recovered from the sea bottom, transported to an onshore base and submitted to this procedure to assure safe and efficient utilization, and the cost/benefit relation of this procedure is very impressive.

It can be seen from the projected composite riser deployment given in Table 2 that it is important to consider the weight and configuration in the design of oil platforms. In an attempt to have lighter deck loads, new offshore platforms, equipment and technologies have emerged. Notable amongst these is the composite pipe risers (CPRs), which were initially installed offshore circa 1995 on the Heidrun Platform as a composite joint (Salama et al., 2002). With the use of composite sections on marine risers, there was a need to ensure the high structural integrity of the structure. As a result of this design consideration, the riser's length has to be proportionate to the water depth or the sea depth. Furthermore, the experience gathered from the offshore deployment of composite risers has enhanced the general understanding of this technology. However, there are still challenges related to the deployment of composite risers and other marine riser systems, including the riser damages,

Table 2
Platform projections for replacement with composite risers.

Year	1st Projected Path	2nd Projected Path	3rd Projected Path
2022		Newer PCSemi	
2021		Newer SPAR	TLP Redeployment
2020		Newer TLP	
2019		Newer TLP	TLP Redeployment
2018		Newer SPAR	
2017		Newer TLP	TLP Redeployment
2016		Newer TLP	
2015		Newer SPAR	TLP Redeployment
2014		Newer TLP	
2013		Newer TLP	TLP Redeployment
2012		Newer SPAR	
2011		Newer TLP	TLP Redeployment
2010		Newer TLP	
2009		Newer SPAR	TLP Redeployment
2008		Newer TLP	
2007		Newer TLP	TLP Redeployment
2006	Current TLP		
2005	Current TLP		
2004	Current TLP		

1st Path- CPRs for remaining wells on current (or existing) TLPs.
2nd Path- Newer platforms for CPRs, considering SPARs and TLPs.
3rd Path- CPRs considered in every well during the redeployment of TLPs.
Single Point Anchor Reservoir (SPAR), Tension Leg Platform (TLP), Paired Column Semisubmersible (PCSemi).
These data were updated and originally projected by NIST, so have been reproduced and updated (Source: NIST, 2005).

failure modes and limitations. As seen in Fig. 5, some SURF projects have recorded a variety of failure incidents reported on marine risers and flexible pipelines. It is observed that external sheath damage is the most common issue on these structures making up 35% of all failures.

With the advancement of new offshore technologies, the design concepts of marine risers have been altered as the depth of hydrocarbon production has increased (C.V. Amaechi et al., 2019). According to Bai and Bai (2005), the lengthwise consideration has to be feasible by saving money on the materials and installation but also has to be flexible enough to allow for considerable floater excursions. The main issue in the design of marine risers, however, is the dynamic structure, which is extremely vulnerable to climatic and operating pressures (Deka et al., 2010), hence, the material attributes are required to conduct items including design analysis, prototyping, qualification and inspections (Hatton 2012, 2015; Salama et al., 2002). Composite riser technologies, as per previous studies, is a promising area in the offshore sector since it offers viable solutions (Baldwin and Johnson, 2002). Researchers proposed cost-cutting strategies without sacrificing CPR quality, based on composite riser analysis. Sevillano et al. (2013) analysed drilling risers using different riser configurations, from 250 m, in intervals of 250 m to 2000 m, by modelling riser lengths that were both without Vortex-Induced Vibration (VIV) straked (or bare) and buoyancy modules. They found nonlinearity exhibited by the risers due to the increase in the riser length during installation until the motion is restricted.

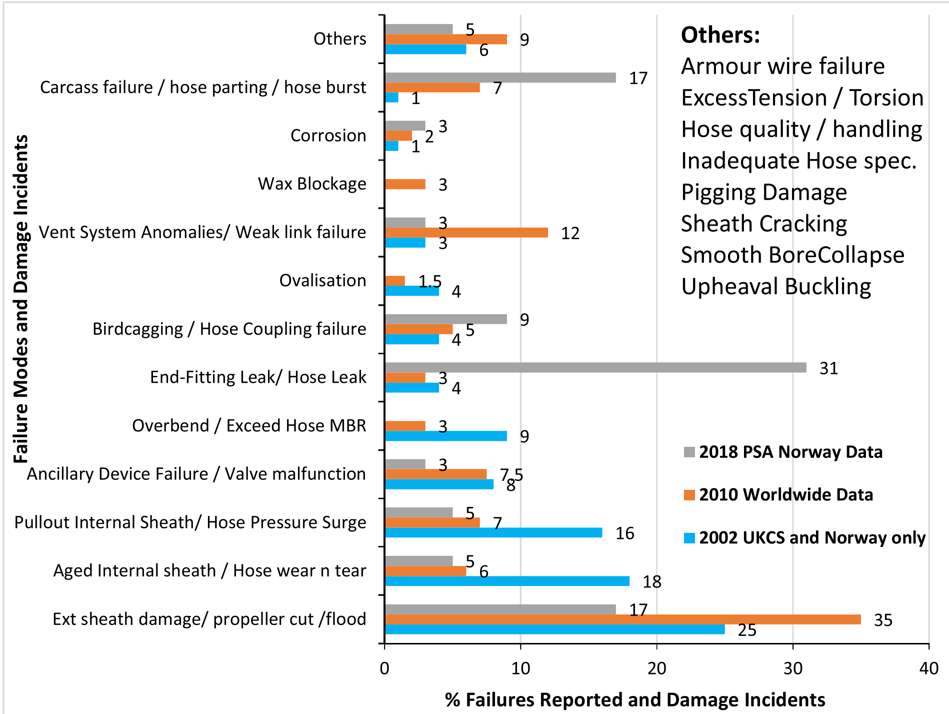


Fig. 5. Reported failure and damage incidents on unbonded flexible pipes and flexible risers (Data sources: PSA and 4 Subsea 2018; Drumond et al., 2018; C.V. Amaechi et al., 2022; Adapted with permission of PSA Norway & Elsevier Publishers).

Carpenter (2016) discussed the method of manufacture used for the Victrex PEEK material matrix and the qualification of composite riser pipes. Hatton et al. (2013) presented a composite pipe as a carbon enabler for offshore applications, demonstrating various test results and limitations with the design, as well as issues with the technology. However, due to the size of the structure, more recent investigations on composite marine risers have been reported as numerical investigations using various methods like finite element analysis (FEA). The representations for the composite riser models from the numerical studies reflected the idealisations in real-life installations, showing various sections of the risers, as considered in the literature (Wang et al., 2015). An example of a typical composite riser model and its configurations is shown in Fig. 6. However, the validation of such models is another existing challenge, although some progress has been made in this area. Andersen et al. (1997) described the design, fabrication and testing of the composite riser system using MODRAN software. Andersen et al. (1998) later conducted a comparative assessment of steel and composite risers planned for a water depth of 3,810 m for 3D dynamic analysis and demonstrated the progress made on an earlier composite riser designed for a water depth of 1,829 m. Valenzuela et al. (1993; 1987) also published comparative performance research on composite drilling risers for 914 m water depth in a GoM environment, demonstrating that while the steel riser must be disconnected after a 20-year storm, the composite riser can remain connected even after a 100-year storm. To minimise the cost of the end fittings, Johnson et al. (1998) presented the manufacturing, development and qualification of a filament-wound CPR that employed a stub ACME thread rather than the specified Hydril MAC-II premium thread. More novel solutions were tried, such as a composite riser joint on a 0.445 m ID workover riser system intended for a 3,000 m water depth that was more cost-effective and could be installed in the absence of umbilicals, through the use of an autonomous control system (Moreira et al., 2003).

3. Design and analysis of composite risers

3.1. Design considerations

The design of composite risers stems from the developments made on flexible risers. Currently, there are more than 3300 flexible pipes (or flexibles) in service, out of which 58% are deployed in installations as flexible risers and 76% of these flexibles operate under design pressures of 345 bar (5,000 psi). Most of these flexibles, approximately 90%, have an internal bore diameter of 10 inches and 70% of all flexible risers are applied in water depths less than 1,000 m (Ha 2016). However, the design temperature of 70% of flexible pipes is less than 80 °C (176°F), which has led to developments in the use of composite materials to achieve better design on marine riser systems. Currently, advancements in the subsea pipeline and riser technology include new options for carcass, liners and increased sour service (Hatton 2012a; Carpenter 2014). OCYAN's CompRiser® design was developed to fulfil the needs of Brazil's pre-salt regions. It is best for deep water settings with depths of 2000–3000 m and sour service conditions. CompRiser® inherits the attributes and capabilities of Magma Global's m-pipe as it provides a great deal of flexibility, strength, high corrosion resistance and low gas permeability for fluids like seawater, carbon dioxide and hydrogen sulfide (Magma 2016; Hatton 2012, 2015). Furthermore, the flexibility of the m-pipe allows for the creation of a novel lower riser termination concept that permits the riser to be directly connected to rigid and flexible flowlines. The CompRiser® inherits a decoupled solution of 7000 tons less load per FPSO (considering 2 towers), using a typical SLHR configuration, as shown in Fig. 7. It was assembled by BrasFELS using high local content compact equipment in the assembly yard under a 30-day duration, and installation offshore usually takes 45 days to complete. There are other similar research developments on composite risers and tubes, as well as various technologies that enable offshore composite technologies (Carpenter 2014). These include the use of composite materials, like carbon fibres with a typical material layup, as shown in Fig. 8. Different marine riser configurations including the conventional configurations are illustrated in Fig. 9.

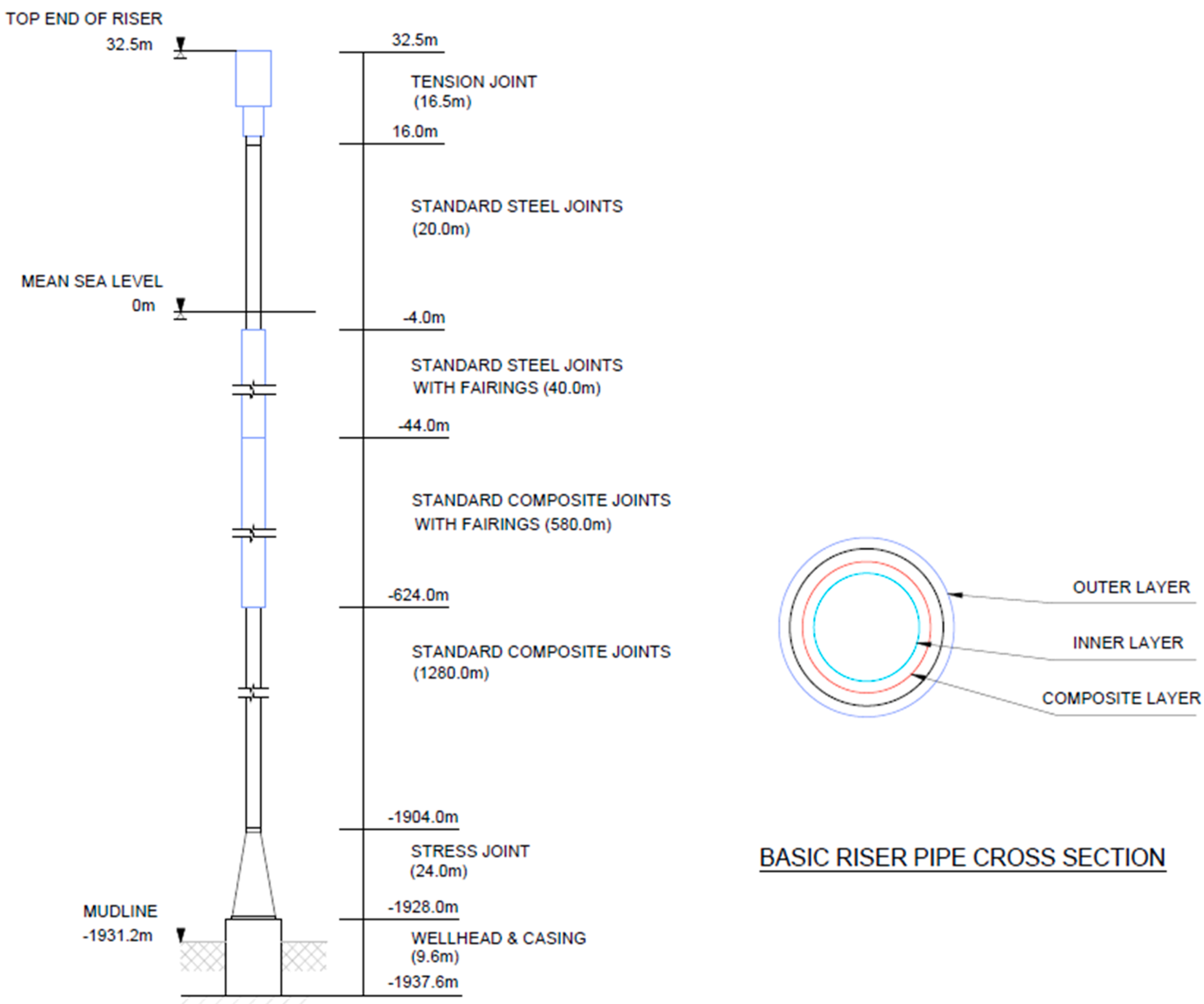


Fig. 6. Schematic diagram of a typical composite riser design with section labels (Adapted from Wang et al., 2015).

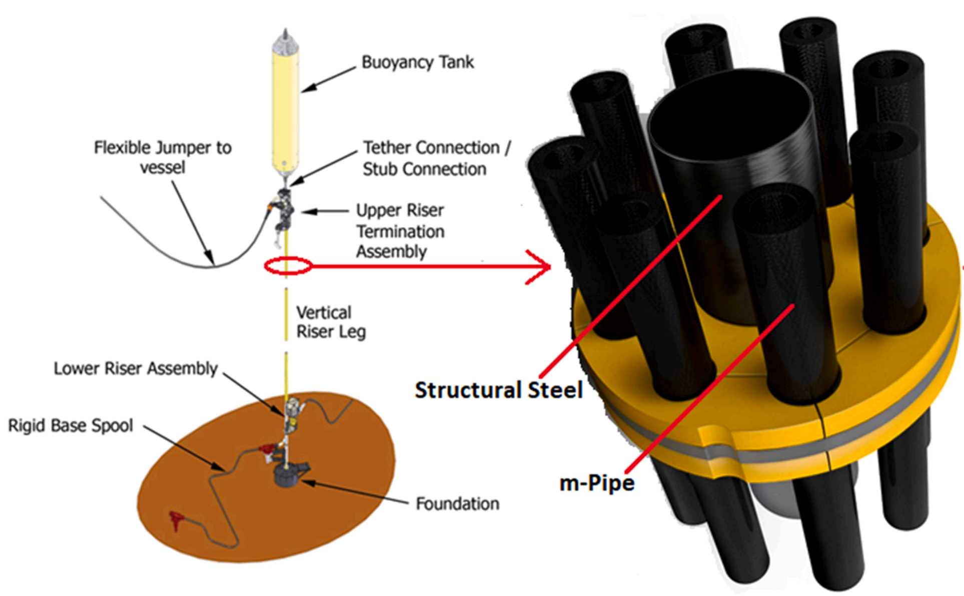


Fig. 7. Configurations of Single Line Hybrid Riser (SLHR) for composite riser using m-pipe.

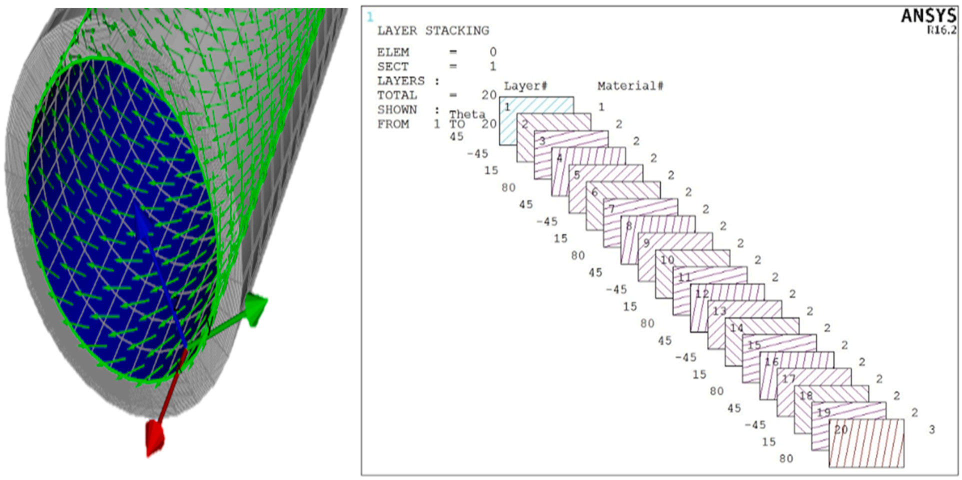


Fig. 8. Typical parametric composite riser model in ANSYS ACP and lay-up in ANSYS APDL.

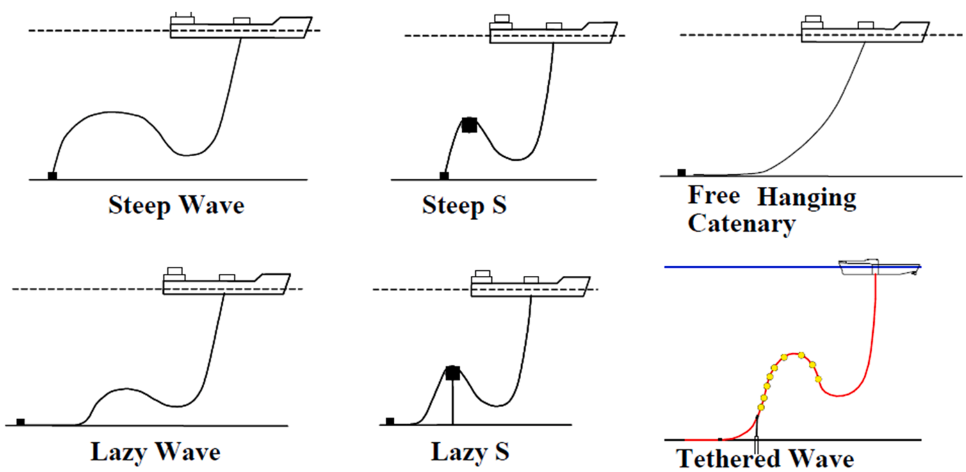


Fig. 9. Schematic diagram of different configurations of marine risers.

Materials like AS4/PEEK have been effectively utilised in the numerical modelling of composite risers (Amaechi 2022; Hatton et al., 2013). This is owing to advancements in polymers and composites, increased composite material availability, and lower composite material costs. Improvements in high-volume production techniques, quality control, the establishment of more design regulations and suggested practices on composite risers are amongst other considerations. Higher safety factors and more severe load conditions must be considered because of the application and design requirements of composite risers. There have been advancements made in both local and global design of composite risers in recent studies (e.g. Edmans et al., 2019, Ragheb and Sobey 2021). Edmans et al. (2019) presented a multiscale approach for designing flexible risers, while Ragheb and Sobey (2021) applied an extensible modelling approach for composite risers. Some recent studies on the structural verification, reliability and fatigue studies of composite risers have also been presented with good findings (Ragheb et al., 2021).

In deeper water, the sea states and vessel characteristics tend to have less influence and fatigue life improves. However, high currents can produce increased bending loading on a riser, leading to lower fatigue life and a reduction in the operating envelope. When designing for deeper water, the wall thickness of the riser tubular may need to be increased to withstand the increased tensile loading, resulting in increased stiffness. As the stiffness of the riser increases, the bending loads become greater and this again reduces the fatigue life. Sea states provide the forcing functions that are applied to the vessel. The vessel characteristics determine the vessel's response to these forces resulting in the vessel's motions. These motions are more significant to the riser in shallower water than deeper water and in combination with vessel offset influence the allowable operating envelope for both riser strength and fatigue life. Sea currents have significant effects on deeper water and cannot be neglected in shallow water either. The currents can vary in depth, magnitude and direction. The larger the diameter of the riser, the greater the loading. In deep water, these loadings can create significant bending loads and fluctuating currents can result in greater fatigue loading despite depth.

3.2. Flexible pipe risers

Flexible pipe risers shall be designed to withstand the most onerous load combinations of functional, environmental and accidental loads selected from the extreme design and fatigue environment. The design of such risers shall be based on proven polymeric materials and meet the requirements of the following considerations:

- Susceptibility to failures such as outer sheath burst due to excessive annulus pressure, abrasion/handling damage, looping, kinking, twisting during installation, unacceptable ovality and crushing, excessive bending, high snap loads, excessive twist and compressive loads during installation, operation and recovery.

- Interference/clashing between the riser and the vessel hull, adjacent risers and mooring lines for all installation and operation conditions.
- Wearing of the moving layers inside the flexible risers and the presence of corrosion by-products.
- Accounting for high and low-temperature requirements over the service life and withstanding associated thermal stresses and thermal cycling, and any limitations related to repeated temperature cycling specified by the manufacturer.
- Ensuring that the riser does not go into compression at any point unless specifically designed to accommodate this compression.
- Assuming that the outer sheath has been damaged and external hydrostatic pressure acts on the outer surface of the subsequent pressure-containing layer.
- The riser and its end fittings shall withstand torsion in both directions without lock-up of the tensile or pressure armour wires "bird-caging" or structural damage.
- Resisting to the axial and radial loads caused by the reverse end-cap effects that may cause bird-caging or lateral buckling failures.
- Considering installation limits concerning the crushing loads combined with the tension and bending.
- The fatigue life and corrosion-fatigue life assessments shall consider all possible annulus conditions.
- Pressure and tensile armour wire fatigue and corrosion-fatigue performance assessments shall be based on material design S-N curves generated with the predicted annulus environments for the service life. The cases which shall be considered are exposure to the operational service annulus environments with permeated gas and condensed water; exposure to air and exposure to seawater.

3.2.1. Extreme response

The global extreme riser configuration design criteria are governed by the load capacities of the components that the system comprises (e.g. riser pipe, bend stiffener and turret I-tube capacity). The design criteria for the calculation of these load capacities are detailed in the relevant codes, standards of the flexible pipes and the datasheet of the flexible manufacturers. The minimum bend radius of the flexible pipe risers should be evaluated where influenced by ancillary components to ensure no overbending (e.g. three-dimensional bending over mid-water arch and localised loading from buoyancy modules).

3.2.2. Fatigue response

The flexible pipe risers shall be designed for a service life with certain safety factors and shall include fatigue loading from different scenarios such as installation, in-place hydro test and in-place operation. Also, the fatigue analysis shall consider accidental cases such as in-place with one mooring line broken either for the FPSO or Buoy (but not both cases simultaneously). The fatigue process in metals is understood relatively well, consisting of a nucleation phase and the growth of a single dominant crack, leading to failure. The fatigue process in the laminate is more complex due to the inhomogeneous and anisotropic nature of the laminate. For instance, during TCP fatigue, the laminate accumulates damage in a more general fashion than at a localized dominant site. Due to the accumulating damage, the residual stiffness and strength of the laminate degrade. The acceptance of fatigue is usually determined using Miner's rule. This rule is used to calculate the cumulative effect of all individual fatigue loads resulting in a percentage of total fatigue life consumed during the service life. All fatigue life calculations shall be performed on material properties and stress levels at the worst-case operational temperature and the material strength allowable corresponding to this temperature is used. Although the fatigue life behaviour of fibre-reinforced polymers is fundamentally different from those of metals, it is a common practice to use the well-known S-N curves and/or Goodman diagrams to estimate the fatigue life. This methodology excels in simplicity and does not need detailed information on the actual damage. Extensive material test data are also required to formulate the S-N curves and Goodman diagrams.

3.2.3. Interference assessment

Interference between adjacent flexible risers and other components of the system is an important consideration in the design of flexible pipe risers. If possible, there shall be no interference/clashing between the riser and the vessel hull, adjacent risers and mooring lines for all installation and design load conditions. Pipe/seabed interaction is permissible. Interference analysis shall be performed to confirm a proposed or dictate a final, field layout for hang-off and seabed layout constraints.

3.2.4. Thermal performance and flow assurance

Thermal performance analysis and flow assurance calculations shall be carried out to assess the thermal performance of the flexible pipe system and determine the required level of insulation. The thermal performance analysis shall determine the overall heat transfer coefficient of the system (U-value) and the associated cool-down time in both thermal steady state and shutdown conditions. Insulation material selection shall be based on performance requirements and shall account for critical parameters such as water depth, temperature and fluid compatibility. The possible impact of the insulation system on overall riser system performance and the associated installation requirements shall be considered when designing the insulation system.

3.2.5. Flow-Induced pulsations

Dry gas passing down the bore of a corrugated riser can generate internal vortices in the flow, which in turn results in dynamic pressure pulsations. If such low amplitude pulsations are coupled to the topside or subsea acoustic resonators (e.g. "dead-leg" small bore connections), a significant amplification of these pressure pulsations can then occur. Actual field-based measurements have shown that dynamic pressure levels of up to 6 bar can be generated under the right circumstances. The forcing frequency of the pressure pulsations increases with the flow velocity in the riser and can cover a range from below 100 Hz to over 2 kHz potentially leading to fatigue failure of the small-bore connections in a matter of minutes and an unquantified effect on the flexible pipe service life.

3.2.6. Other issues

Flexible pipe risers shall incorporate gas venting systems irrespective of gas permeation rates. There should be a minimum of two vent ports coming out of the end fitting. Flexible pipe risers shall also be designed for pigging, and the manufacturer shall recommend the types of pigs suitable for the specified pigging operations. The manufacturer shall also define and advise any limitations on the type of frequency and conduct of pigging operations through the riser system.

3.3. Analysis considerations

3.3.1. Local cross-section tools

The requirements of the local cross-section tools of composite risers are as follows:

- Predict stress and strain in each pipe layer for each load condition combining internal loadings (e.g. pressure and temperature) with globally applied loadings (e.g. tension and bending).
- Predict hydrostatic and mechanical collapse of the cross-section, including the effects of pipe curvature and collapse of intermediate layers as appropriate (e.g. smooth bore tube collapse).
- Assess reverse end cap effect and lateral wire buckling.
- Predict fatigue armour wire stresses from combined tension and bending loads.
- Assess the creep of polymers into adjacent armour layers and within the end-fitting including gap span analysis to determine the maximum allowable interlock gap.

- Determine the heat transfer coefficient of the cross-section. Local cross-section analysis software tools are in general proprietary tools developed and owned by the manufacturers. The local cross-section analysis can be designed using the following design approaches:

Approach-1. An analytical or computational approach, i.e. stress/strain levels at all relevant parts of the structure are determined employing stress analyses (e.g. FE-analyses or analytical model) and compared with the relevant data on the mechanical strength.

Approach-2. Design by component testing only, i.e. full scale or scaled-down samples of the structure or parts of the structure are tested under relevant conditions such that the characteristic strength of the complete structure can be determined.

Approach-3. A combination of FE or analytical approach and full-scale testing. Tests under this category are carried out to verify that the assumptions on which the design is based are correct and that no important aspects of the design have been overlooked. Verification tests should be carried out to compensate for the following issues:

- Incorrect description of or an unsatisfactory large uncertainty in the failure mechanisms.
- Incorrect description of load combinations or corresponding large uncertainties.
- Incomplete understanding of the effect of the environment.
- Lack of experience with similar structures or components.
- Uncertainty in the accuracy of modelling.
- Unknown effects of large-scale manufacturing procedures.

3.3.2. Global configurations

Global configurations analysis is usually performed to evaluate the global load effects on the composite risers during all stages of installation, operation and retrieval, as applicable. The global configurations analysis is influenced by interference considerations. Depending on criticality, consideration of wake effects may also be required. Several wake effect models have been developed in the literature and calibrated for riser applications. The following types of global configurations analysis should be performed:

- Preliminary design and frequency screening (extreme and wave-frequency fatigue): frequency domain or time domain (regular wave).
- Detailed design (extreme and wave-frequency fatigue): frequency domain or time domain (regular wave or random sea). In general, the conservatism of the frequency domain approach should be demonstrated using time domain analysis, whereas the conservatism of the regular wave approach should be demonstrated using random sea analysis.
- Vortex-induced vibration (VIV) design.

3.3.3. Pressure sheath diffusion

Permeation analysis shall be performed to determine the annulus gas composition and the required wire material grade(s); assess corrosion/corrosion fatigue; and predict annular flow rates for the gas venting system. Permeation analysis is also required to predict the pressure build-up between sheaths in multi-layer constructions.

3.3.4. Fabrication and installation

The effects of fabrication and installation operations shall be accounted for in the design of the riser system. The installation analysis shall establish the functional requirements for installation equipment, operational sensitivities, limiting conditions and key hold points. The installation analysis shall be performed to validate the proposed installation procedure and demonstrate the integrity of the riser and the associated equipment during each specific phase of the installation activities. The following issues, in particular, shall be assessed:

- Installation loads (e.g. maximum and minimum tensioner loads, if applicable, friction loads, etc.).
- Limiting sea state and current profiles for deck and installation activities.
- Stress/strain during deployment/recovery.
- Fatigue damage due to installation operations.
- Interferences and clashing during installation.
- Possible permanent deformations and consequences on the riser integrity.

3.3.5. Flow assurance

Flow assurance analysis shall be carried out to assess flow deliverability, hydrate potential, wax deposition, slugging potential and operability of the riser system across the life of field conditions. Flow assurance analysis shall consider the following issues:

- Dynamic steady-state (hydraulic and thermal) analysis of the wellbore, flowline and riser system from the reservoir through to the topsides separator/slug catcher. This predicts operating conditions in the production system and establishes preliminary line sizing, insulation requirements, slugging potential, gas lift requirements, and hydrate and wax formation potential.
- Transient analysis to ensure adequate understanding of the pipeline operation during the change in production over the life of the field. Typical transient events to be considered are slugging, shutdown, startup, depressurisation, pressurisation and pigging. Transient analysis facilitates the detailed system definition and determination of operating philosophies, liquid handling requirements, and wax and hydrate management strategies.
- Wax deposition analysis to determine the amount and rate of deposition of wax.

3.3.6. Global modelling

Specialist commercial computer programs can be used for global modelling analysis. This approach treats the riser cross-section as a single equivalent pipe and does not explicitly model the various structural layers that are dealt with in the local analysis models. Using the single equivalent pipe approach, the structural characteristics of the risers are represented by axial stiffness, mass per unit length, bending stiffness and torsional stiffness.

3.4. End-Fitting

End-fitting design of composite risers has also evolved (Toh et al., 2018; Bertoni F. 2017; Hatton et al., 2013) and different methods of high-pressure dependant and unique features have been developed. However, they all serve a similar function, either as couplings, end connections or end terminations. A very important aspect of the design of composite risers is the manufacture of the end-fitting (see Chen et al., 2004, 2016). For composite tubes, one can incorporate flanged joints or end-fittings that are weldable. In an earlier design of the end fitting, a method that transferred bending and torsional loads into the overwrap was conceptualised and built upon. Earlier prototypes used composite tubular structures that were rated as high-performance with many structural layers that worked independently and were placed within the matrix of its resin. Different methods of end-fitting design have been developed in recent years and Fig. 10 shows a list of some end-fitting designs.

Tamarelle and Sparks (1987) proposed a model employing a composite tube of 25 m lengthwise, manufactured via filament winding, to show the tubes' practicality and performance. The authors noted that using composites proffered cost-savings and provided a solution to the

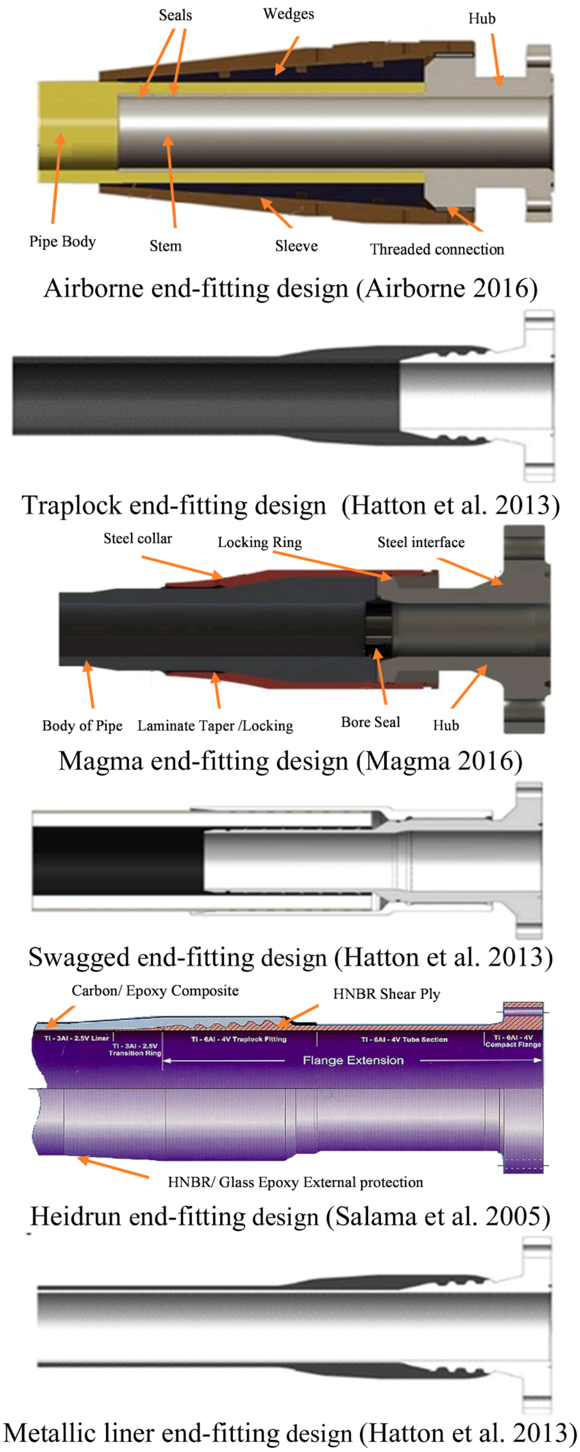


Fig. 10. Example of end-fittings designs for composite riser assemblies.

offshore difficulties of corrosion, weight and fatigue. On a TLP, the authors also used 0.244 m (9.625″) ID-steel instead of the standard 0.223 m (9″) ID-35 MPa composite riser pipe casings. The apparent weights were 981 N/m and 440 N/m, respectively. This resulted in savings via the tubes' flexibility and low weight, leading to low top tension. Consequently, the amount of steel in the hull, deck load and platform area were reduced. New developments in composite riser pipes and their end fittings have been made, according to Hatton et al. (2013), but the challenge remains that steel and composites are different materials with different coefficients of thermal expansion, thermal conductivity, Poisson ratios and stiffness.

While examining the Metal Composite Interface (MCI) of the end-fitting on the riser pipe, it was observed that failure can occur at the interface or even when externally loaded, especially if it is heated. This is confirmed in the study by Toh et al. (2018), as depicted in Fig. 11. The designer must guarantee that the final fitting can retain its tightness. Fig. 11 also shows the failure envelopes of all models investigated by the researcher. These failure envelopes are calculated using a series of combined loading cases on the riser pipe body without an end-fitting and used to present the representative failure disparities for different end-fitting models. It can be seen that the critical loads for the steel riser are within the failure curve, implying that a certain safety margin is guaranteed. Two failure curves based on liner yielding and composite failure are displayed separately for the thermoset composite riser. The yielding curve of the liner is similar to that of the composite laminate, indicating that the liner is strong. Since the liner is significantly stronger than the composite laminate, it can withstand a lot of weight, especially when the riser joint is under axial tension. Materials with low modulus and high strength should be used for the liner to fully apply the high strength of composite materials. The composite laminate failure curves of Models 7 and 8 are separated into two segments with a kink between them. The axial tension dominates the tensile failure of carbon fibre in the axial direction, as described via the upper segment. The lower segment describes the externally induced compression failure of carbon fibre along the hoop direction.

Hatton et al. (2013) proved that the carbon fibre/PEEK pipe to be a potential candidate for offshore applications by applying an axial load of 23.9 MPa as operational pressure load, 42.75 MPa as test pressure load and internal pressure load of 38.3 MPa. The authors also took into account the end-fitting development process. The most popular technique, known as the Trap-Lock end-fitting, was patented by Baldwin et al. (1997b), as illustrated earlier in Fig. 10. It has a metallic mandrel wrapped in a composite material. Wilkins (2016) demonstrated a revised Magma m-pipe design that incorporates fibre and matrix of Victrex PEEK to make a composite laminate. Kalman et al. (1999) also researched a flexible riser with a bore diameter of 0.232 m, designed as an unbonded system operating under 1,500 m sea depth. The riser had tapes, extruded thermoplastic and metallic strips with helical winding. Employing 16 dynamic and 10 static load scenarios in his investigation, Kalman et al. (1999) discovered that the light material satisfied the same specifications as a steel riser. However, this modelling approach depends on the loading conditions and material of the composite riser, such as composite thermoplastic tubes (Picard et al., 2007; C.V. Amaechi et al., 2019; Wang et al., 2015, 2017).

3.5. *Qualification*

The qualification of composite risers has been a major industrial challenge, however, has progressed in recent studies. Meniconi et al. (2001a) presented a study on composite riser pipe behaviour and concluded that while constructing a CPR joint, three factors must be considered: composite tubular design, MCI design and metal connection design. Composite pipes have been considered in the industry application of composite risers by Magma Global and Airborne Oil & Gas. This is understandable because the composite pipes require more benchmarking to be fully deployed as composite risers. Thus, most configurations use hybrid composite risers, or composite risers with configurations such as SLWR and composite pipes suspended from buoyancy tanks or having buoyancy floats on the pipes with marine continuous bonded hoses (C.V. Amaechi et al., 2019). The selection of materials for the composite marine risers has been identified as also important in both the design and qualification stages. Carbon fibre materials have been utilised in some reported studies due to their strength in tensile and compressive directions, amongst other mechanical characteristics. An example of such carbon fibre composite material mix is seen in the utilisation of AS4/PEEK carbon fibre for composite marine riser, which can be considered as a complimentary factor in the

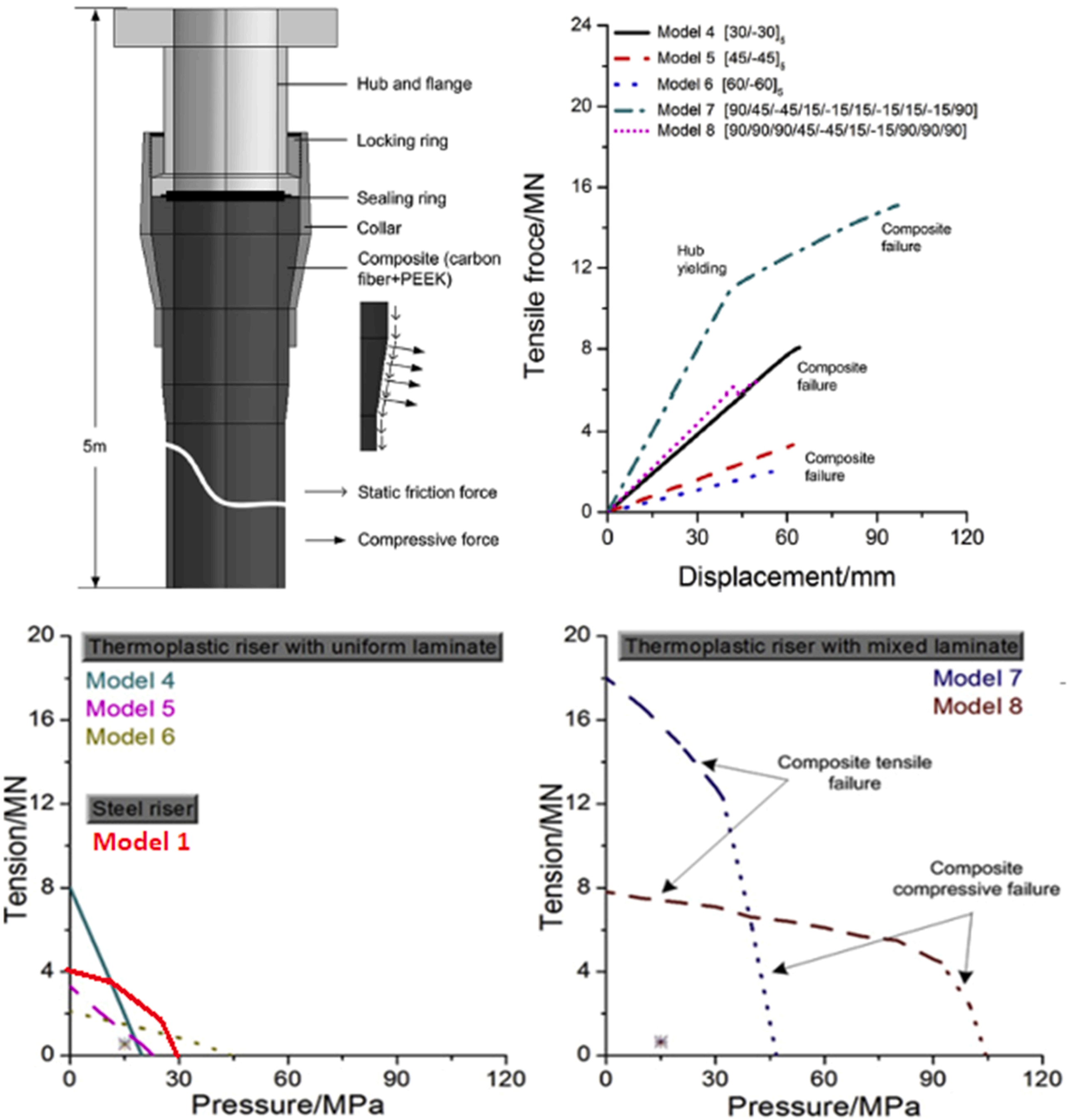


Fig. 11. Results of displacement versus force profiles for several end-fitting design models incorporating the load transfer mechanism of magma end-fitting (Adapted with Permission; Publisher: Elsevier, Source: Toh et al., 2018).

design (Amaechi et al., 2019; Amaechi and Ye, 2017; Hatton 2012). In another study, Cheldi et al. (2019) presented the application of composites on TCP pipes for spoolable reinforced pipes designed for transporting water. Strohm (formerly Airborne Oil & Gas) qualified their TCP pipes with the TCP qualification status given in Table 3 and the DNV qualification flowchart shown in Fig. 12 for technologies such as reinforced spoolable TCP pipes and composite risers (DNVGL-RP-A203, 2019).

4. Benefits and limitations

4.1. Benefits

There is great potential for composite riser systems, offshore composite materials, composite chokes and kill lines, and composite tethers. They are valuable in industry, academia and research institutes, despite the numerous hurdles they face. Aerospace composite research has led to the development of offshore composite applications. Wave, excess pressure, internal pressure, manufacturing problems, MCI, end-fittings and steel weight are all issues related to offshore construction. The use of composites has revealed several benefits, however, the thickness of the wall must be considered because HPHT is involved, and the weight of other lines such as flow lines, choke lines and death lines all contribute to the overall weight of the riser joint assembly system. To lower the top tension stress on the riser system, lightweight materials have been determined to be necessary (Omar et al., 1999; Hatton, 2015). These advancements have the potential to lead to more high-strength and cost-effective composite risers, lightweight composite drilling

Table 3
Strohm's TCP material qualification status. (Adapted with Permission. Source: Airborne Oil & Gas, now Strohm).

Polymer	PA12	HDPE / PE	PVDF
Fibre	Carbon	Glass	Carbon
Temperature	≤ 80 °C	60–65 °C	≤ 121 °C
Pressure raing	15 ksi	10 ksi	15 ksi
Pressure Rating	High pressure	Medium pressure	High pressure
Track Record	Temporary and permanent applications	Permanent applications such as hydrocarbon fluid/ gas	—
Qualification Status	DNVGL qualification completion Q1 2019	DNVGL qualified	DNVGL qualification completion Q2 2019

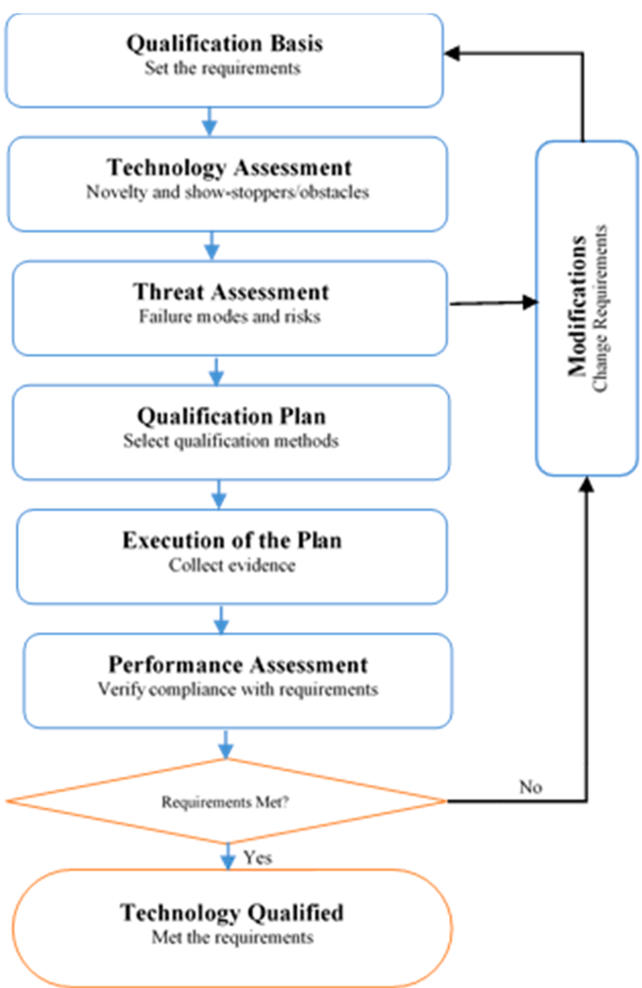


Fig. 12. DNV risk-driven processes for qualification of technologies like composite riser (DNVGL-RP-A203, 2019).

risers, lower drilling costs, lower field development costs, the extended service life of competing systems by lowering top tension, reduced deck loads on platforms, allowing weight on deck for new equipment and better-enabled production in the future. CPR has the potential to be deployed on better-equipped production platforms with dry-tree capabilities, such as SPAR (Single Point Anchor Reservoir), TLP (Tension Leg Platform) and PCSemi (Paired Column Semisubmersibles).

Qualifying the cost of composite risers has been compared to that of steel in material, design and installation aspects and mechanically, based on effectiveness. In an earlier study by Salama et al. (2002), it was stated that the first application of composite technology in an oilfield was to reduce the weight of the loads, accompanied by the fact that the price of composite materials was decreasing. Carbon fibres cost $50/kg when JIP projects began in the mid-1980s, but were around $14/kg in the 2000s. This was still higher than the $0.60/kg price of steel at the time (Salama et al., 2002). As such, the cost of composite materials affects the economic impact of the composite riser, for its design, testing, qualification, production and full-scale utilisation. Table 4 summarises the findings of the composite riser comparison research against other applications.

4.2. Limitations

Although the development of composite risers has seen some remarkable advances in recent times, they also have limitations. One of the limitations is that the composite risers cannot be used in highly sour environments. Also, current applications of composite risers require supporting structures and are thus often configured with hybrid configurations or combined with steel. Another common failure for composite risers is abrasion, which occurs when the riser comes in contact with other supporting frames, guard rails, bending stiffener supports, end-fitting connectors, moonpools, riser tensioners or platform bodies. One more limitation of composite risers is the structural verification and reliability (Wang 2013; Amaechi, 2022; Chiachio et al., 2012; Du, 2005; Ragheb et al., 2021b). Recent studies have been carried out on the reliability of different offshore structures including composite risers (Ragheb et al., 2021), offshore inflatable barriers (Aboshio et al., 2021), composite structures (Carneiro and António 2019; Chiachio et al., 2012), flexible pipes (Liu et al., 2018) and mooring lines for single point mooring (SPM) systems (Eghbali et al. 2018). As such, it has been recommended that every composite riser is accompanied by a reliability analysis and structural verification to check the correctness of the design. In addition, structural verifications could also be conducted using unique experimental techniques on marine structures (C.V. Amaechi et al., 2022). There are also many compression limitations and

Table 4
Benefits and prospects of composite riser systems.

Composite Choke and Kill Lines	Composite Risers	Composite TCP Pipes
Have less weight than steel lines	Have improved corrosion resistance	The low weight of pipes
Have increased mud flow rate and better well control	Offer lower life cost and lower system cost	Applicable for spooling as TCP spools
Have excellent fatigue performance	Have high-pressure capability	Ease of deployment
Can have increased inner diameter of choke and kill lines with the same weight	Reduces the variable deck load	Ease of installation
Store more riser joints on the deck	Ease of transport and deployment, like towing on site	An alternative to composite risers
Extend the operational envelope of existing drilling rigs	Offer reduced weight of buoyancy and reduced size	
Reduces the variable deck load	Have a smooth bore for a higher flow rate	
	Reduced subsea project risk	
	Requires no upper riser assembly for deployment	
	Enable drilling operations in ultra-deepwater and high reservoir pressures	
	Have excellent fatigue performance	
	Lightweight (m-pipe is 1/10th of steel in air and 1/5th in water)	

associated failures of composite risers. There is presently no industry-accepted standard for determining compression limits in a subsea cable. As a result, most manufacturers now stipulate those subsea cables may not be axially stressed in compression. Furthermore, there are no industry guidelines on the effects of producing compression forces within subsea cables and the subsequent effect on cable integrity. There is also no information in industry-recommended practices and guidelines about experimental test arrangements for determining permitted compression values within a subsea cable. Due to a lack of modelling and testing advice and manufacturer recommendations for zero compressive loads within subsea cables, the design criteria for subsea cable utilisation and installation have been unnecessarily conservative and restricted (Reda et al., 2016). Another limitation aspect of composite risers is the interface between layers of the pipeline and contacts between the riser, anchorage, seabed inclinations and supports (Reda et al., 2018, Reda et al., 2019; Cox et al., 2019; Menshykov and Guz 2014). Some other studies have been presented and showed that matrix cracking should be checked on the composite risers and similar composite tubes (Xing et al., 2015; Wang et al., 2021; Bai et al., 2015; 2015b; Amaechi et al., 2022; Wang et al., 2017).

4.2.1. Common failures

The marine structure is composed of multiple layers and contacts between different materials, each with different layer thicknesses. Current industry developments on composite risers have been identified in deep waters, such as that in Brazil, where there are ongoing projects to replace the failed flexible risers with CRA-lined risers. There is another project reported in literature (MagmaGlobal, 2015, 2016; C.V. Amaechi 2022) called the OCYAN hybrid composite riser project with Magma Global's m-pipe. This solution called *CompRiser* as a cost-saving composite riser with M-pipe's decoupled solution that is lightweight, having 7000 tons less load per FPSO (considering 2 towers) in a collaboration between Technip's Magma Global and OCYAN (see Fig. 13). Both collaborators accomplished completing the design of another design called the Composite Multi-Bore Hybrid Riser (CMHR) for ultra deep fields. According to Ocyan (2018), the companies have entered into a long-term commercial relationship with one another, and they submitted a joint bid to handle the CMHR developmental initiatives for deep water in Brazil. The design had been verified by an independent engineering firm, and the company had engaged in discussion and analysis with prospective customers. The CMHR provides a number of benefits, many of which address obstacles that operators face (Ocyan, 2018; Palmigiani 2018). The FPSOs of today are under constant pressure to lower their weight and load capacities. Considering it is a decoupled solution, the CMHR applies fewer than twenty (20) percent of the loads that are applied by other solutions; this results in a weight differential of up to nine thousand (9000) tonnes per floating production storage and offloading unit (FPSO) (Ocyan, 2018; Palmigiani 2018). Currently, the authors were unable to identify any of the composite marine riser applications or practical adaptations for composite riser systems that have not reported any recent failures.

This review also looked at the design, deployment and manufacturing aspect of composite riser systems to identify any failures. Given its excellent resistance to corrosion (for instance, caused by CO_2 and H_2S), low weight, and capacity to tolerate high temperature and pressure, TCP is frequently used in modern manufacturing. Its adaptability makes it possible to build a novel idea for the lower riser termination assembly (which already has a patent and is undergoing the final review process). This concept enables a direct connection to be made between the risers and the flowlines, regardless of whether the flowlines are flexible or steel, without requiring a redesign of the CMHR. The CMHR was outlined to make use of Magma's m-pipe, which can be fabricated in a more condensed, straightforward, and standardised manner by virtue of the fact that it is reeled into reels and does not require welding (Ocyan, 2018; Palmigiani 2018). It was reported that it will allow for a greater percentage of locally sourced materials, but after all the CMHR components have been delivered to the designated yard, the assembly of the CMHR takes only twenty (20) days (Ocyan, 2018; Palmigiani 2018). They further reported that it will only take another twenty (20) days offshore to finish the installation, and there will be no need for a specialised vessel, and the risk of being exposed to the elements will be kept to a minimum (Ocyan, 2018; Palmigiani 2018). However, not much information is currently available in public domain on the current status of this technology which has been adopted.

Furthermore, earlier sections have discussed some of the issues operators face in determining the integrity of the composite risers. It is recommended that pipeline monitoring sensors be deployed on composite risers. Within this past decade, some earlier reviews on composite risers, TCP pipes and marine composite hoses have made related findings (Pham et al., 2015, 2016, Toh et al., 2018). Several case studies of significant abrasion of subsea cables, umbilicals, marine hoses, and flexible risers have been documented in the literature (Marinho et al., 2007; Amaechi et al., 2021, C.V. 2022; PSA and 4Subsea 2013, 2018). These technical reports showed different failure behaviours which may

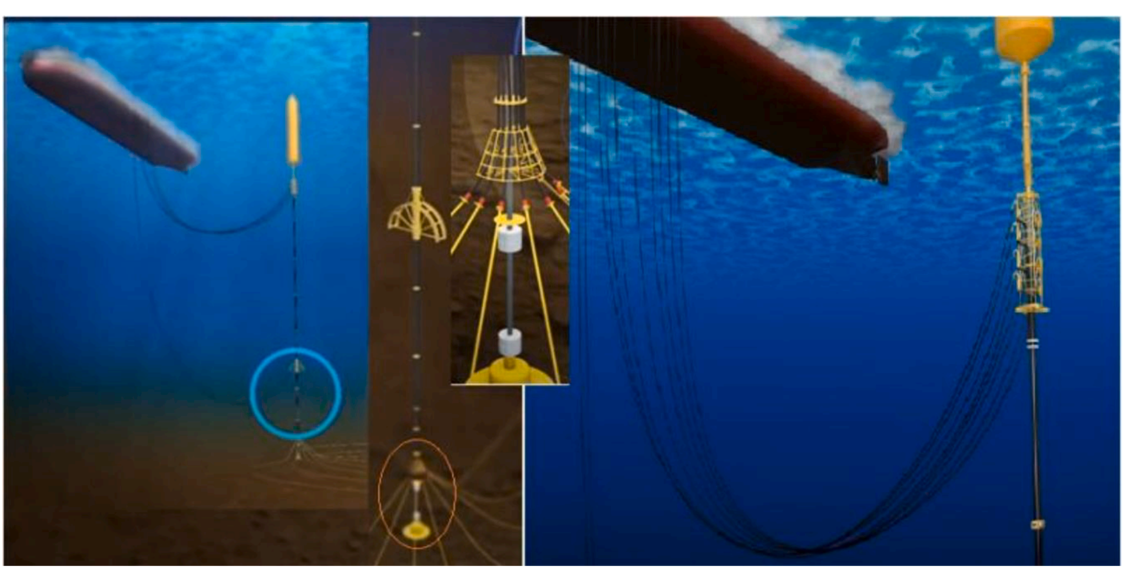


Fig. 13. CompRiser as cost saving composite riser with M-pipe's decoupled solution that is lightweight, with 7000 tons less load per FPSO (considering 2 towers) collaborated by Technip's Magma Global and OCYAN (Adapted with permission, Source: MagmaGlobal 2016).

be studied alongside the corrective actions taken.

In the marine oil and gas sector, SURF facilities entail subsea umbilicals, risers and flow lines, which include composite risers. Submarine cables have been used in a variety of industries, including power transmission and communication, all over the world. Umbilical lines have been commonly used to transport treatment fluids for control and production from the platform to the underwater wellhead. The umbilical is one of the most important components of a complicated subsea system as it provides the system's life support. However, marine riser, marine hose, submarine cable and composite riser failures can have serious economic and technical consequences as well. Current methodologies for composite risers and submarine cable design concentrate on the ultimate limit states, which include structural integrity, number of layers, reliability analysis and on-bottom stability. When the integrity of the armour sheathing is damaged, it can cause abrasion of the outer protective layers, i.e. yarn and extruded sheaths, as shown in Fig. 14(a). These failures can gradually lead to damage and failure of subsea cables and composite risers (Reda et al., 2021a, 2021b; Wang et al., 2021; Marinho et al., 2007; Reda et al., 2021a; Drumond et al., 2018; C.V. Amaechi et al., 2022).

An increasing number of failure issues on marine risers with composite configurations have been shown to include failure from collapse pressure due to outer sheath failure (see Fig. 14(b)). Other representative failure modes are failure from burst pressure, delamination of the layers of the composite riser and carcass failure for hybrid flexible composite risers (Gillet 2018; Wang 2013; Chesterton 2020; Butler 2021; C.V. Amaechi 2022). Hence, it is recommended that proper design checks are conducted with necessary tests for different loadings, using specified recommendations from industry standards and guidelines. The findings and recommendations from recent studies on the failure of composite risers are also helpful resources (C.V. Amaechi et al., 2022). In addition, these recent studies should be considered in elaborating on necessary standards to forestall these common failures.

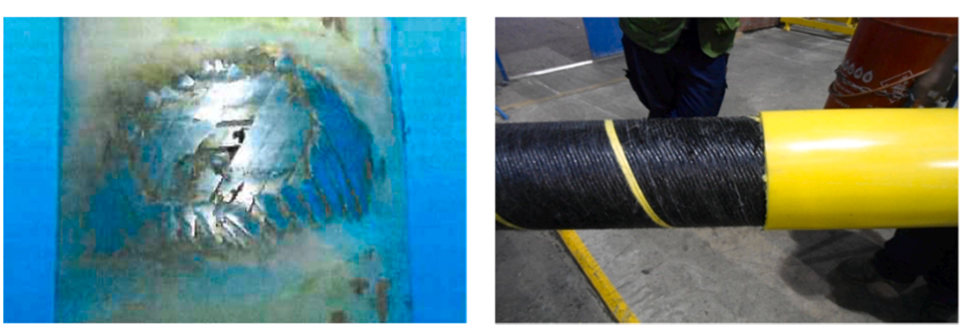
4.2.3. Issues with the application

Numerous concerns and challenges regarding composite risers have been identified in various investigations. These challenges range from design issues, standardisation issues and complexity, to interoperability, as given in Table 5. The first barrier to overcome is product qualification. Since composites are often flammable, fire protection should always be considered, thus special attention should be made when selecting insulation materials. Another critical consideration is the composite riser's installation, as installations in ultra-deep seas necessitate more caution, experience and knowledge, as concluded by Hutton TLP in the United Kingdom. It should be highlighted that the experience and expertise gained from Hutton were employed in Heidrun TLP (Salama et al., 2002). The Heidrun TLP featured 56 drilling and production slots, 8 export riser tie-in porches and 8 dual-purpose slots, weighed 2290,000 kg (2290 tonnes), and measured 51 m x 38 m x 6 m in a mean sea depth of 345 m on the Norwegian continental shelf. The Jolliet Tension Leg Wellhead Platform (TLWP) in the Gulf of Mexico, which is 536 m deep, is another platform that was built on the original TLP's experience and knowledge. According to a study on the world's deepwater developments (Penati et al., 2015), due to the increased finding of deep water fields and the steady growth in oil recovery, there has been an evolution from shallow seas to deep waters. To tackle the challenges of high flow-rate velocity, corrosion, and deep water erosions, there has also been a rise in novel designs, more versatile installation containers, and the use of unique materials.

Composite riser systems experience several obstacles that limit their

Table 5
Issues and aspect considerations on composite risers.

Issues	Aspect Considerations
Durability	Misconception on durability, eg. for plastics because of the notion that 'metals are tough'.
Repair System	Very little technology on composite risers repair systems, as they mostly have common repair systems.
Cost of composites	The high cost of using composites affects their use in composite risers.
Composite challenge	Composites are combustible; have smoke-liberation characteristics
Technical Innovation	Technical innovation in metals has been established, but few in composites since metals and steel have been utilised for a long time, whereas composites have not.
Failure and Fatigue	The failure/fatigue modes on composite laminates and composite risers
Riser Monitoring	Riser monitoring and the type of sensors to use
Configuration	The global design of composite risers have limited configurations to deploy, such as SLHR configuration.
Interoperability	Using the metal-to-composite interface (MCI) considering that the composite matrix has a different orientation and structure
Scalability	Accommodation of monitoring devices; accommodation of more composite riser joints.
Efficiency	Optimization of composite riser parameters.
Complexity	Concerns with monitoring and control functions; interdependence between composite riser joints and composite risers; modeling, design and analysis of composite rises.
Consistency	Consistent demand response; quality monitoring; controlled production of composite risers; consistent less weight advantage over traditional steel risers.
Standardisation	Harmonization of standards and other recommended practices on composite risers; limited standards exist on composite risers- BSEE, DNV, API and ABS.
Installation	The challenge with the installation of the composite risers especially in ultra-deep waters.
Qualification	There is a challenge with the qualification of composite riser technology.
Design	Requires more analysis (local and global) of composite risers; composite riser technology has a short history compared to steel; lack of a complete design data book on composites generally and on composite risers specifically.



(a) Tensile armour wire rupture (b) Outer sheath failure

Fig. 14. Images of common failure on the composite riser and related technologies, showing (a) tensile armour rupture caused by abrasion (Marinho et al., 2007) and (b) outer sheath failure (Reda et al., 2021a).

use in offshore operations. One of the issues of composite risers is their length, which necessitates more time in manufacturing, as well as better end fitting care and the risk of MCI during manufacture. Recent studies on composite risers have shown the need for qualification on the body and end fittings (Baldwin et al., 1997a; Chen et al., 2004, 2016; Roberts and Hatton, 2013; Salama et al., 1998, 1999). There is also a need for design codes for composite risers, as well as greater manufacturing capabilities for long-length composite risers and more possibilities to deploy composite structures in field development projects. Another obstacle is that each oil field has its unique set of challenges, thus the design of each composite riser must be suited to a specific platform and oil field, taking into account the various water depths. Riser loss due to blow-out is another issue that can affect the design and implementation of composite rises. The blow-out preventers (BOP) on the seabed provide a path for mud return and direct the re-entry of the drill string into the well during drilling, thus it is important to think about how the BOP will be employed to avoid accidents (Weiss, 2010; Randall et al., 2007). Drilling operation cannot be performed in the case the riser is lost during drilling. The riser loss could be caused by a variety of events, including abnormal strength, collapse, abnormal pressure, abnormal twisting, blow-up, disconnect, mechanical causes, abnormal bending, tensioning system failure, lateral constraint, and others. One of these issues, according to Moreira et al. (2003), is that building an in-riser system is more challenging than planning for an open sea riser system as it requires fitting different control elements, such as Batteries and Subsea HPU, all in a much smaller space. Another challenge is that the fire performance of composite risers must be well understood because composite materials are combustible. As a result, close attention should be paid to the material selection of composite risers, particularly in cases where the blowout preventer might fail, which could be due to a bend in the composite riser due to intense pressure from the composite riser when blocked or a draught from the composite riser when blocked. Another issue with using composite risers in deep waters is that ultra-deepwater reservoirs have high temperatures, high pressures, and low natural flowability, all of which can limit their utilisation. Finally, there is a challenge in both fitness-for-service and structural integrity assessments, such as on steel risers which use API 579 (2000) but proffer limited utility for composite risers, which considerDNV (2010).

4.2.3. Monitoring of hybrid configurations

Recent advances in composite risers have been reported to include hybrid configurations called hybrid flexible composite risers. Periodic examinations have revealed a high rate of degradation to the top section of hybrid flexible composite risers, which could compromise their structural integrity and lead to a variety of failure modes. External sheath damage, corrosion and/or fatigue-induced damage to the tensile armours, and torsional instability are the most common of these problems, which can occur during installation or, more commonly, during operation (C.V. Amaechi 2022; Reda et al., 2018, A.M. 2019). Surface monitoring strategies such as percolated gas monitoring, nitrogen injection in the annular space, deformation monitoring, and visual inspection through a video camera, are being implemented for a continuous hybrid flexible composite riser integrity assessment, in addition to the inspection programme, to mitigate the progression of these damages. Alternative systems have been proposed, such as alternative torsion monitoring, tensile armour stress measurement, tensile armour wire rupture detection by acoustic emission, and exterior sheath wrinkling monitoring via optical fibre sensors. The outcomes of field experience are reported in Marinho et al. (2007), which describes and evaluates these strategies. Damage to hybrid flexible composite risers during installation or operation results in significant expenses, not only for the replacement of damaged lengths but also, in some cases, for the oil and gas production losses caused by failure. The implementation of an integrity evaluation programme was prompted by the need to preserve the structural integrity and operational continuity of flexible pipes, which are critical in oil and gas production, well management, and monitoring. The periodic inspections of the hybrid flexible composite risers are carried out by abseilers from the riser/platform connection down to the water surface, and by submarine-certified inspectors from the water surface down to a water depth of 30 m (Marinho et al., 2007). The authors reported that their survey was carried out using a remote-controlled vehicle (ROV) and saturation divers from this depth down to the riser/flow connection. There is thus a need for more sophisticated monitoring technologies and techniques. Surface monitoring techniques are being employed for a continual integrity assessment due to the high incidence of damage along the hybrid flexible composite riser's top portion.

5. Conclusions

This paper presents a state-of-the-art review of composite marine risers for offshore platforms. The advantages of composites in developing marine risers for deep-sea were examined from several angles, including the design, manufacture, applications, analysis techniques, industrial standards, potentials and problems. This review portends that there are clear benefits to using composites in the design and development of marine risers, including the lower cost of maintenance, resistance to corrosion and lightweight gains (i.e. platform weight reduction and lighter equipment of riser development and fabrication). It was also found that composite materials can be crucial in the drive towards deepwater operations and tougher environments. However, it has to be noted that the use of composite riser systems in offshore operations was found to be limited due to several issues. Firstly, the length of the composite risers requires more time in the manufacturing process. Secondly, composite risers require customised end-fitting to suit their operation environment, thus requiring some careful attention. Thirdly, due to the multi-layers of the composite risers, there are production challenges based on the Metal-Composite Interface (MCI). Fourthly, composite risers are usually designed with composite laminates matrix, and as such it is necessary to investigate the matrix cracking. Fifthly, composite risers have not been fully qualified due to issues related to different design requirements, material choices, environmental conditions and seawater conditions (such as in pre-salt areas). Thus, composite risers pose a challenge in developing standards and design codes for such a technology, however, existing details provide good guidelines for use in academia, research institutes and industry. Within the offshore industry, such details enhance the future growth of CPR technology. Lastly, there is also a necessity for performing more full-scale tests to qualify for larger sizes, which would increase the prospects of deploying composite risers for operational developments on offshore installation activities. In summary, the techno-economic benefits established for composite marine risers are reflected by the rising research trend with future directions for both academia and industry.

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CRediT authorship contribution statement

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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