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Review

Review of Composite Marine Risers for Deep-Water Applications: Design, Development and Mechanics

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Abstract: In recent times, the utilisation of marine composites in tubular structures has grown in popularity. These applications include composite risers and related SURF (subsea umbilicals, risers and flowlines) units. The composite industry has evolved in the development of advanced composites, such as thermoplastic composite pipes (TCP) and hybrid composite structures. However, there are gaps in the understanding of its performance in composite risers, hence the need for this review on the design, hydrodynamics and mechanics of composite risers. The review covers both the structure of the composite production riser (CPR) and its end-fittings for offshore marine applications. It also reviews the mechanical behaviour of composite risers, their microstructure and strength/stress profiles. In principle, designers now have a greater grasp of composite materials. It was concluded that composites differ from standard materials such as steel. Basically, composites have weight savings and a comparative stiffness-to-strength ratio, which are advantageous in marine composites. Also, the offshore sector has grown in response to newer innovations in composite structures such as composite risers, thereby providing new cost-effective techniques. This comprehensive review shows the necessity of optimising existing designs of composite risers. Conclusions drawn portray issues facing composite riser research. Recommendations were made to encourage composite riser developments, including elaboration of necessary standards and specifications.

Keywords: composite riser; pipeline; marine riser; marine composite; marine structures; composite structures; advanced composite material; thermoplastic composite pipes (TCP); fibre-reinforced composites (FRP); hybrid composite structures; review

1. Introduction

In recent times, the utilisation of marine composites has grown in popularity [1–5]. This has been considered both as full thermoplastic composite pipes (TCP) or as hybrid composite structures [6–10]. Particular applications of composites are seen in researches on composite risers [11–13]. The reason is that composites differ from standard materials such as steel in a number of ways, and more marine designers now have a better understanding of composite materials from flexible risers [14–16]. Secondly, these composite materials have weight savings and comparative stiffness-to-strength ratio, which could be advantageous in marine engineering [17–19]. Thirdly, the offshore sector has grown in response to newer innovations in composite structures, such as composite risers [20–22]. In principle, more subsea developments enhance successful drilling operations and provide new cost-effective techniques. Thus, marine risers are crucial components of all subsea production systems, termed SURF (subsea umbilicals, risers and flowlines) [23–27]. In composition, composite tubulars like marine hoses and composite risers are composed of various layers, with internal and external polymer sheaths to ensure internal fluid and exterior sea water integrity [28–33]. To ensure the reliability, vortex-induced vibration (VIV) and fatigue studies have been conducted on SURF structures under global loadings and deep-water conditions [34–37]. Figure 1 presents some floating deep-sea offshore platforms and marine riser configurations.

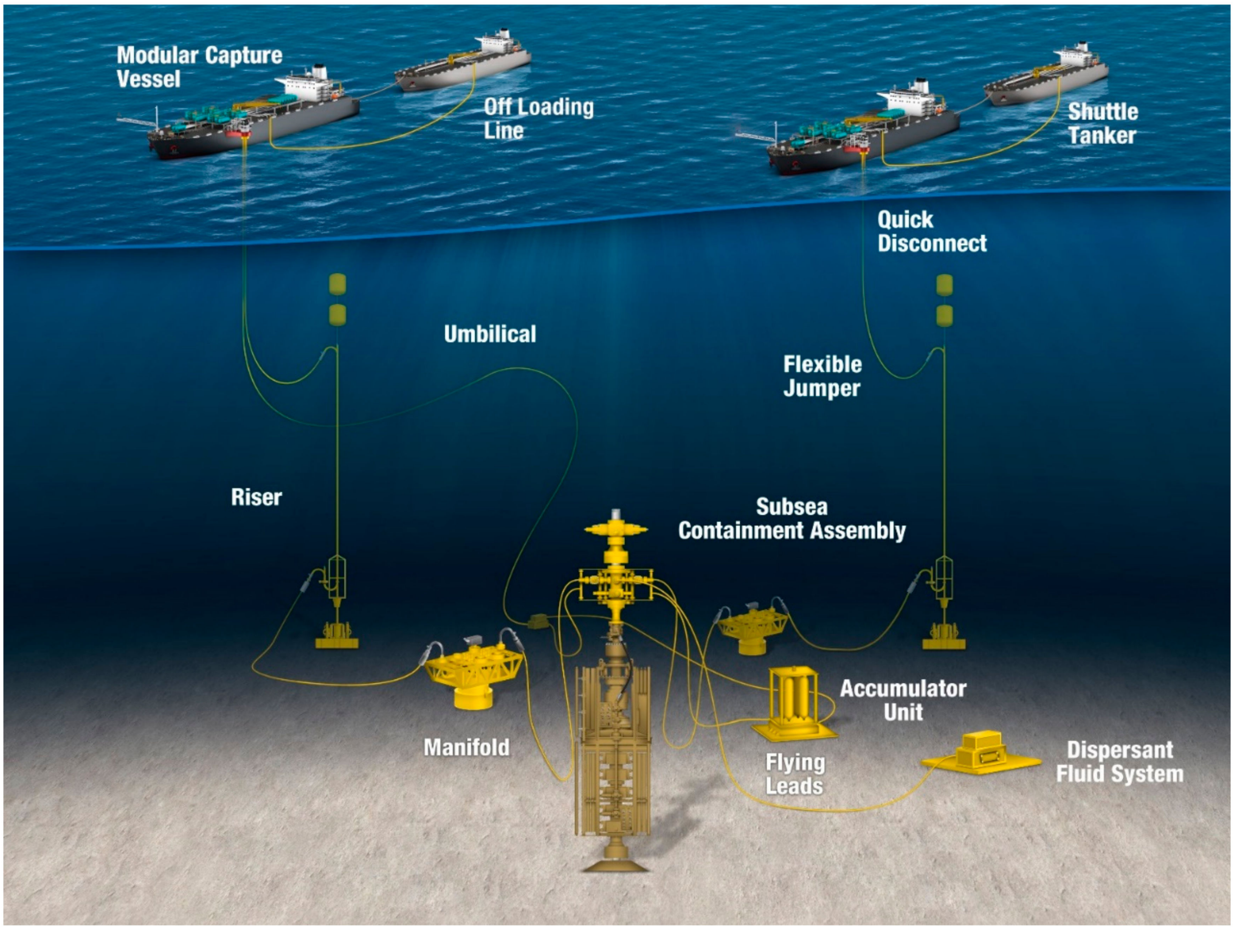

Figure 1. Deep-water facilities showing offshore platforms with the configurations for marine risers. Fluids are directed from the well to the Modular capture vessels (MCV) via flexible pipes and risers in a cap and flow system, which are part of an expanded containment system. (Courtesy: Marine Well Containment Company (MWCC)).

At extreme depths around 3000 m, the risers are induced by external loadings, corrosive fluids, increasing pressures, changing temperatures, etc. [38–43]. As such, it is important to effectively test these composite production risers (CPR) against test limits of steel catenary risers (SCR) and other bonded composite pipes to avoid failure of the marine riser [44–47]. Composite production risers (CPR), hose-lines, pipelines and flowlines, convey hydrocarbons as fluids and production ingredients [48–52]. These fluids include injection fluids, control fluids and gas lift. Risers are primarily used to move fluids or gas from the seabed to a host floating platform or onshore facility or to a transfer vessel [53–55]. However, risers are affected by vibrations and thus require tensioners designed for the control of marine risers [56–58]. Different failure modes have also been recorded on marine risers [59–64]. Additional riser functions, depending on the application, include: conveying fluids between the wells and the floating, production and storage (FPS) units. The fluid types include production, injection, importing, exporting or circulating fluids used for operation between the FPS and remote equipment or pipeline systems; guiding drilling or workover tools and tubulars to the wellbore as well as into the wells; supporting auxiliary lines; and serving as, or incorporating, auxiliary lines [65–67]. However, these ISO standards do not cover composite riser design and analysis. Typical composite riser joint (CRJ) is seen in Figure 2. Developments made are also detailed in Table 1.

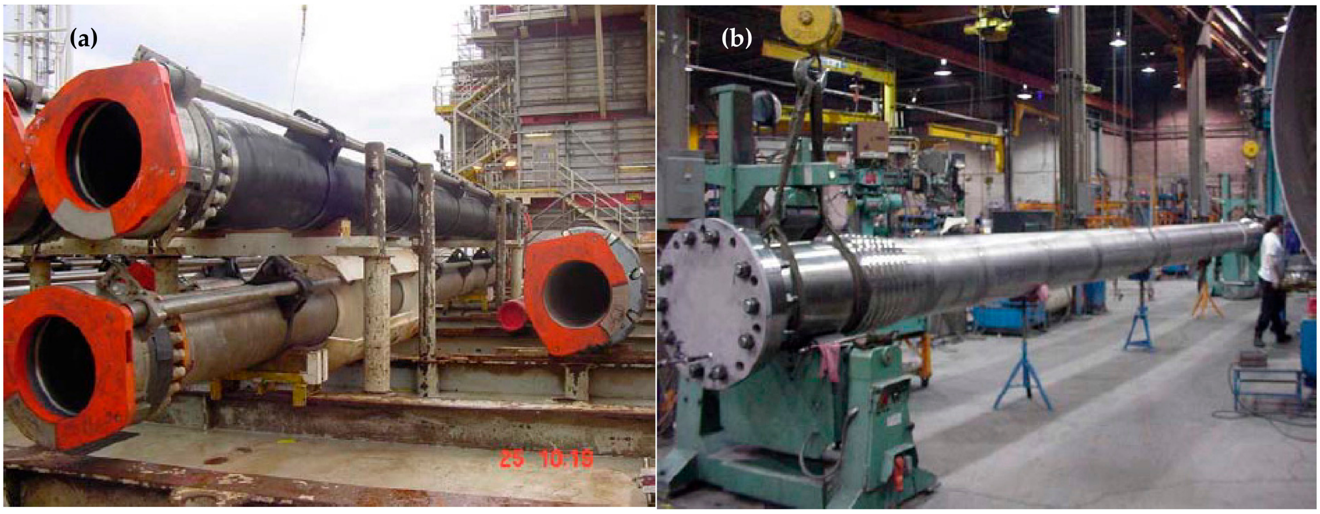

Figure 2. The stack of Norske Conoco AS and Kvaerner Oil Field Products (NCAS/KOP) composite drilling risers (CDR) which held the first composite riser joint (CRJ) for Heidrun Platform with an assembly of titanium liner connector. (**a**) CDR Joint Located Over Titanium Drilling Riser Joint, and (**b**) Titanium Liner-Connector Assembly of NCAS/KOP Composite Drilling Riser (Courtesy: OTC's OnePetro Publisher; Norske Conoco AS; and Kvaerner Oil Field Products; Sources: [66,67]).

Table 1. Historical summary of previous joint industry projects on composite risers.

Year	Project Funder/Country	Reference	Riser Type	Materials	Thickness (mm)	ID (m)	Length (m)
1973	Ahlstone Marine Riser	[67]	D	Glass fibre/epoxy	–	–	–
1985–1987	Joint industry program (JIP) by Institut Francais du Petrole and Aerospatiale du France/France	[68,69]	P	Glass and carbon fibres/epoxy	9.57 (carbon) 7.28 (glass) 1.1 (inner layer)	0.2286	4 and 15
1994–2000	National Institute of Standards and Technology (NIST)'s Advanced Technology Program (ATP)/US	[70–77]	D&P	Carbon fibre & E-glass fibers/epoxy	Not specified	0.496/0.255	2.286
1995–1999	JIP—ABB, Vetco Gray and University of Houston.	[78–81]	D	Carbon fibre/epoxy	Not specified	0.5	Not specified
1996–2001	JIP—ABB, Vetco Gray, Aker Kvaerner, Conoco, EU Thermie, Chevron, Hydro, Statoil, Shell and Petrobras/US	[82–85]	D	Carbon fibre/epoxy	Not specified	0.5	Not specified
1999–2000	JIP-NIST/ATP, Shell & BP-Amoco/US	[86,87]	D&P	Carbon fiber/epoxy		0.250	19
1995–2001	CompRiser JIP—Heidrun CDR joint by Norske Conoco AS and Kvaerner Oilfield Products/Norway	[88–92]	D	Glass and carbon fibre/epoxy	Not specified	0.536	14.585
2003	JIP-ConocoPhillips, Kvaerner Oilfield Products & ChevronTexaco/Norway	[93,94]	D&P	carbon fiber/epoxy	Not specified	0.55	14.7
2007	Doris Engineering, Freyssinet, Total and Soficar	[95]	P	Carbon fibre/epoxy	–	–	–
2006–2009	Part of NIST Advanced Technology Program by University of Texas/US	[96–104]	D	Glass and carbon fibre/epoxy	30.5	0.540	4.57
2008–2011	Research Partnership to Secure Energy for America (RPSEA)/US	[105–110]	D&P	Glass and carbon fibre plus epoxy	25.4 (liner) 53.3 (composite)	0.508	10
2009	JIP—Airborne Composite Tubulars, MCS Advanced Subsea Engineering & OTM Consulting	[111–115]	D&P	Glass & carbon fiber/epoxy	Not specified	Not specified	Not specified
2011-date	Magma Global of Technip FMC/UK	[116–126]	D&P	Carbon fibre/epoxy	7–39	0.047–0.6	Up to 27.4
2011-date	Airborne Oil and Gas (now Strohm)/Netherlands	[127–136]	D&P	Glass and carbon fibre/epoxy	Varies	Varies	Varies
2011-date	University of New South Wales/Australia	[9–11,137–148]	P	TCP, carbon fiber/epoxy & PEEK	Varies	Varies	Varies
2015-date	Lancaster University/UK	[12–15,149–155]	P	carbon fiber/epoxy & PEEK	Varies	Varies	Varies
2017-date	University of Southampton/UK	[156–162]	P	carbon fiber/epoxy	Varies	Varies	Varies
2013-date	National University of Singapore/Singapore	[159–165]	P	carbon fiber/epoxy	Varies	Varies	Varies

P—production riser, D—drilling riser, CPR—composite production riser, CDR—composite drilling riser.

As seen in scholarly works and industry research on composite risers as tabulated in Table 1, more novel methods have been employed in recent times. Historically, the progress made in this field was magnified when the first CPR joint was installed on Heidrum Platform in 2002 [88,89], as depicted in Figure 2. Some designs guidelines for marine risers were also given in standards. An earlier analysis of several marine risers, with design methodology, was published in the API 16J Bulletin ([166]), which has been replaced and developed into recent standards like the ISO 13624 [167,168], ISO 13625 [169] and ISO 13628 [170–179], and API [180–184]. Moreira et al. [185] investigated a 0.445 m-ID workover riser system built for a 3000 m water depth and deployed it, excluding any umbilical via an autonomous control system. The findings from earlier studies, application of these standards and advances made led to other cost-effective composite riser joint. In another study, Cederberg [109] found that composite riser joints had common issues that arose were autofrettage and the metal–composite interface on the CPR joint. Similar findings have been examined in different models [78,100–103,114,186–190].

These studies conducted on the stress analysis of composite riser joint and its composite tube showed that there is a connection between the end-fitting and the composite tube. As such, optimisation is recommended to obtain the best orientations, lay-up angles, number of layers, type of materials to use, fibre design, matrix design, resin-coating material, etc. These include investigations on the microstructure of the composite materials conducted to ascertain different failure modes and material strengths of these novel materials. Notable industry players in recent times in the field of composite risers include Magma Global of Technip FMC [191,192] and Airborne Oil&Gas (now Strohm) [193,194]. Some qualifications were achieved in recent times on composite riser and TCP tubes. Magma Global had qualified a composite riser tube earlier in 2013, while Airborne Oil & Gas qualified some TCP pipes circa 2017. In the later, the qualified composite riser was deployed as the first subsea TCP flowline to use hydrocarbon fluid services efficiently by Airborne Oil & Gas. Similarly in the former, OCYAN and Magma Global have also effectively configured m-pipes on CPR for pre-salt Brazil, as depicted in Figure 3.

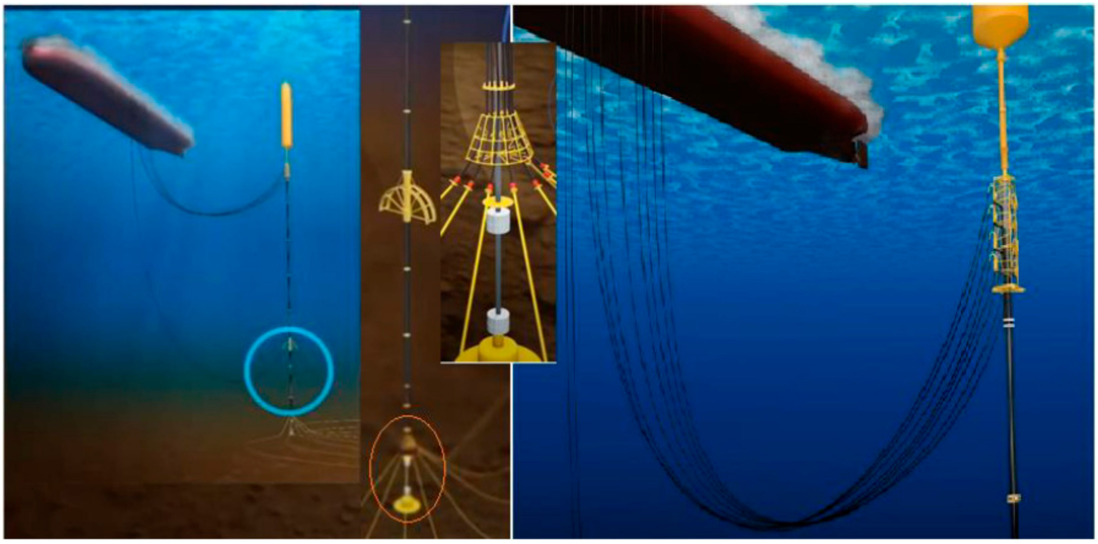

Figure 3. CompRiser as cost-saving composite riser with m-pipe's decoupled solution, which is lightweight, with 7000 tons less of load per FPSO (considering 2 towers) in a collaboration between Magma Global and OCYAN. (Reproduced with permission obtained from Magma Global to reuse image of m-pipe application).

This has also led to advances in the use of TCP pipes on composite risers and related marine composite tubulars for water injection, transport, product transfer and loading and fluid discharge services [31,51,150]. Based on numerical models presented on different CPR models of well-validated composite risers with safety profiles from results of the stress analysis, conducted in ANSYS APDL [137–142] and ANSYS ACP [143–146,149–152], respectively. Additionally, both researchers used different platforms—while the former used a TLP (tension leg platform), the later used a SPAR (single-point anchor reservoir) and a PCSemi (paired-column semisubmersible). However, both models reflected different novelties in modelling approaches and showed that the full application of composites is feasible using multilayered composite structures and effective liner material for layering the structure. Other comparative investigations on steel risers and composite risers have revealed that composite risers offer numerous benefits, particularly a low weight and cost savings [65,98–104,195–199].

Thus, the aim of this review is to conduct a comprehensive overview on the design, developments, and mechanics of composite risers, including their end-fittings, for offshore marine applications. Section 1 presents an overview of the current position on composite risers within the offshore industry, in comparison to related existing applications of composite materials in deep waters. Section 2 presents the design with detailed analysis of the advances in composite riser research for deep waters. Section 3 presents studies that reflect the mechanical behaviour including fatigue. It also includes findings from selected studies on analytical, numerical and experimental studies on composite risers. This study presents the merits and demerits on the application, qualification and utilisation of CPRs.

2. Design and Manufacture

In this section, the advances in mechanics, design, modelling and qualification of CPRs are presented.

2.1. Advances in Composite Risers

Composite materials for offshore applications were first introduced about seven decades ago. They have piqued the interest of the offshore oil and gas industries, owing to their high specific strengths and stiffnesses, which help with weight reduction and cost savings. Earlier investigations on composite risers have been conducted and showed good results [68–76,88–91]. However, composite applications in composite risers have transiting barriers and are thus seen as an enabling technology [65,119]. Composites are currently used in different components such as accumulator vessels, composite tethers, flexible risers, tensioners, buoyancy cans and the topside of platforms as well as on flow-lines, spoolable tubings, spoolable pipes, buoyancy modules and buoyancy floats [5,55,83,200–205]. However, their application in risers has been limited to prototype production and drilling risers to date, despite that they may significantly reduce the weight of deep-water operational systems [93,94,105–110]. Although the material costs of FRP composites are higher than those of steel, many previous studies have shown that their total life-cycle costs will be lower due to the add-on effects of their weight savings for other system components. These components include the reduced stacked volume of BOP, reduced total system weight, top-tension requirements, mooring pretensions, reduced platform sizes and buoyancy weights [55,110]. An increased water depth implies that there will be larger platform payloads and additional load conditions which might be severe, necessitating significant increases in the amount of manufactured steel needed as well as extra mooring pretensions. According to some estimates, a one-pound increase in platform payload costs an additional four to seven dollars [55,199]. The top tension required to apply to a riser grows as its operational depth increases, necessitating more buoyancy in the hull and a larger platform. Due to the increasing hydrostatic pressures experienced, both the needed length of the riser and its thickness increases.

As a result, increasing depth has a two-fold influence on a riser's weight and, as a result, the top tension required. According to research, the size of TLPs increases at a considerably faster pace as their top tension increases [200–202], limiting the number of risers that can be used or the depth to which they can be used [206–210]. Based on the present capabilities, the maximum depth to which a steel riser can be deployed cheaply depends on the available platforms. For production risers, between 1000 and 1800 m is a good range, while drilling risers require depths exceeding 3000 m [23–27,41]. As a result of the weight savings from composite risers, more risers can be built at existing depths attributable to the use of FRP composite materials [211–220]. Also, production and the viable utilisation of petroleum resources will increase to even lower depths by using composites [221–230]. In addition to having a lower density, FRP composites have a higher strength-to-weight ratio [231–240]. Excellent damping, thermal insulation and corrosion and fatigue resistance will result in greater savings by lowering maintenance costs by using composites [241–251]. However, appropriate testing and qualification is required to successfully use composite materials in marine risers. It is also necessary to evaluate the durability of the product in sea water. In the research by Venkatesan et al. [252], carbon-fibre-reinforced polymer (CFRP) composites were observed to have long-term qualities after being exposed to clean water and sea water at the same time, with noteworthy differences under various temperatures. Many researchers also concur with the finding that the CFRP's long-term tensile strength is lowered to between 80% and 95% of its original value in the short term [252–258]. It was also discovered in another study by Bismarck et al. [58] on the evaluation of the carbon/PEEK thermoplastic composite that although its axial tensile strength was unaffected by boiling water, its transverse tensile strength was affected. After being exposed to boiling water, the tensile strength of the material was reduced. It was determined that, in order to avoid failure, thermoplastic composites must have a maximum service temperature that is far below certain polymer matrices' glass transition temperatures. Aside from carbon fibres, there are other fibres, such as glass and aramid, and other synthetic high-performance fibres, such as Toray, Spectra, Dyneema, Zylon, M5 and Victrex PEEK, that are also often used in composites. Nonetheless, the choice of material for subsea conditions (such as water ingress) is sensitively dependent on the performance of composites reinforced with these fibres because a reduction in tensile strength can lead to a severely reduced performance of the composite tubular [259–265].

In addition to studying the mechanical properties of composite materials in sea water, there are effects from fatigue, load distributions, global responses and performances of the full-length composite riser. However, the CPR tube, its stress joint, steel tension joint and other standard joints face global functional and environmental conditions [98,143–146,266]. The effects of functional loadings have also been studied in comparative studies presented on both steel and composite risers, including vortex-induced vibrations (VIVs) and resonances on the CPR [11,55,199–202,246]. Generally, it was discovered that as the water depth increases, the tension force diminishes, and the maximum tension force is reached. The stress joint at the bottom bears the brunt of the bending moment, followed by the joints across the surface of the sea, called the mean water level (MWL), displaying larger bending moments than those in the riser string's midsection [98,101,200–203]. However, when it was compared to an all-steel riser, the axial stress and bending were significantly reduced along a composite riser's full length, comprising tension, standard and stress because of its smaller total weight, it had fewer joints. The fantastic fatigue resistance of FRP composites, particularly carbon-fibre-reinforced composites, contributes to their significance. In principle, the structural composition of the CPR tubular body and the composite riser joint is predicted to have an indefinite fatigue life, depending on the material composition, whereas those of the joint's metal liner, the metal–composite interface (MCI), the steel tension joint and stress joints have been proven to be adequate. It is noteworthy to state that the fatigue characteristics of FRP composites can vary, with respect to the basic materials selected and the manufacturing technique used, whereas the fatigue life of its steel liner welds can be significantly reduced. Based on the VIV and resonance investigation on CPRs, some studies reported a resonant response reflecting that the composite riser's response is due to the high resistance of the system in sea water, as it showed no noticeable resonance in comparison to the steel riser [98,266]. Kim [98] showed that the drag force and vibration amplitudes in its bottom section were very small. This implies that the vibration waves were significantly more damped as they descended from the top of the composite riser than they were as they descended from the top of the composite riser in the steel riser. The fundamental frequency of VIV in composite risers was discovered to be less due to its comparative lower mass, but that its worth was relatively insignificant [98–104]. This behaviour was confirmed in some recent studies [143–146] showing that the fundamental frequency of VIV in composite risers was lower due to the stiffness property of a composite riser because the composite riser was sensitive to structural damping and tension fluctuations. Generally, the VIV could be reduced by increasing tension and damping in the composite riser. According to Omar et al. [200], the maximum VIV strains created in a composite riser were nearly half the weight of a comparable steel riser, indicating that composite risers are more durable. Steel risers have a far shorter fatigue life than aluminium risers. An investigation on VIV and fatigue was demonstrated on composite risers by Huang [203] and opined that in the composite riser, the damage produced by both long-term and severe currents was moderate compared to that inflicted to the riser lacking VIV suppression. However, the addition of strakes could assist in the suppression of VIV with efficient suppression control. As a result, strakes are typically utilised with caution to provide an extra margin of safety in such situations involving VIVs.

The benefits of FRP composites are obvious from the explanation above. Due to their superior qualities, such as high specific stiffness, they have advantages over steel. Thy have high corrosion resistance, fatigue resistance, improved thermal insulation, superior damping and a light weight, resulting in improved global responses and performances. In addition, they have better VIV distributions, better fatigue, better bending profile, better stress distribution and better tension distributions along the length of riser responses. However, these are dependent on the materials chosen for the CPR, the global loading and CPR configuration. These attributes also result in a lower cost, easier installation and a longer service life. However, these factors make composite risers efficient by reducing deck loads, lowing platform size, reducing mooring pretension, reducing top tension, reducing system weight, reducing buoyancy weight and the stacked volume. Since all these factors contribute to a lower total cost, they make composite risers more cost-effective. Furthermore, several design variables, including the liner thickness, the fibre and matrix combinations, stacking sequences, composite lamina thicknesses and fibre orientations, can be modified to customise (or tailor) the design of a composite riser to specific requirements. A customised design that fully optimises these variables can improve the benefits of FRP composites and achieve larger weight reductions [79–81]. Figure 4 depicts a summary of the areas of composite risers reviewed herein.

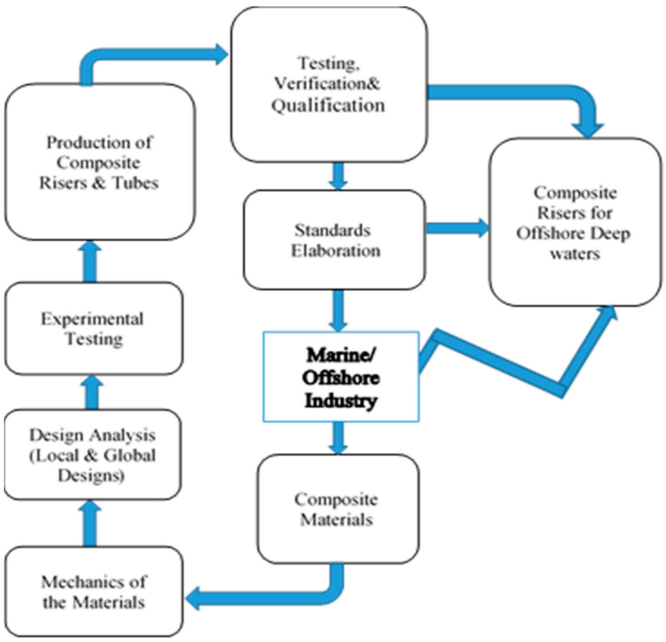

Figure 4. Reflection on sections and aspects covered in this composite riser review.

2.2. Qualification of Composite Risers

Figure 5 shows typical designs of TCP composite pipes, showing model cross-sections from Airborne Oil&Gas and Magma Global. Both pipe designs use TCP materials and have been qualified. Based on different experiments on composite tubes and composite risers, there are attempts to qualify composite tubulars hence elaboration of related standards and regulations by DNV [267–275]. These standards and other presentations on the qualification of TCP composite pipes and composite risers that led to the development of the DNVGL-RP-119 standard [84,85,275]. However, there are still more challenges concerning the qualification. According to an offshore market report on flexible pipes by Lamacchia D. [217], flexible pipes with an inner diameter (ID) of 4–8 inches account for 80% of all flexible pipe applications, as shown in Figure 6. For numerous years, the flexible market limit has been set at PxID = 80,000 psi.inch, with high pressure–high temperature (HPHT) flexible risers qualified up to 20 ksi by TechnipFMC. The bulk of flexible tubing in use has a PID value of less than 50,000 psi-in, which is noteworthy.

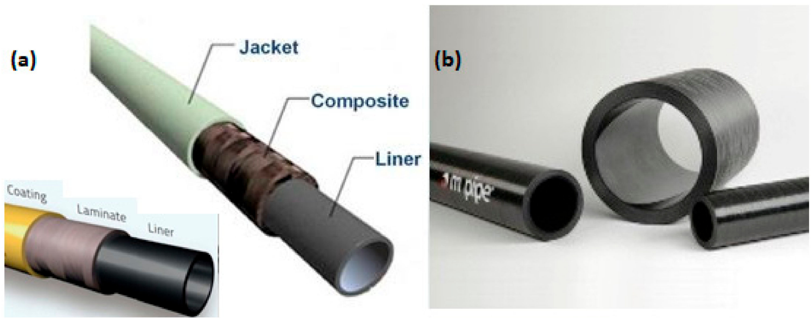

Figure 5. TCP composite pipes by (**a**) Airborne Oil&Gas, and (**b**) MagmaGlobal.

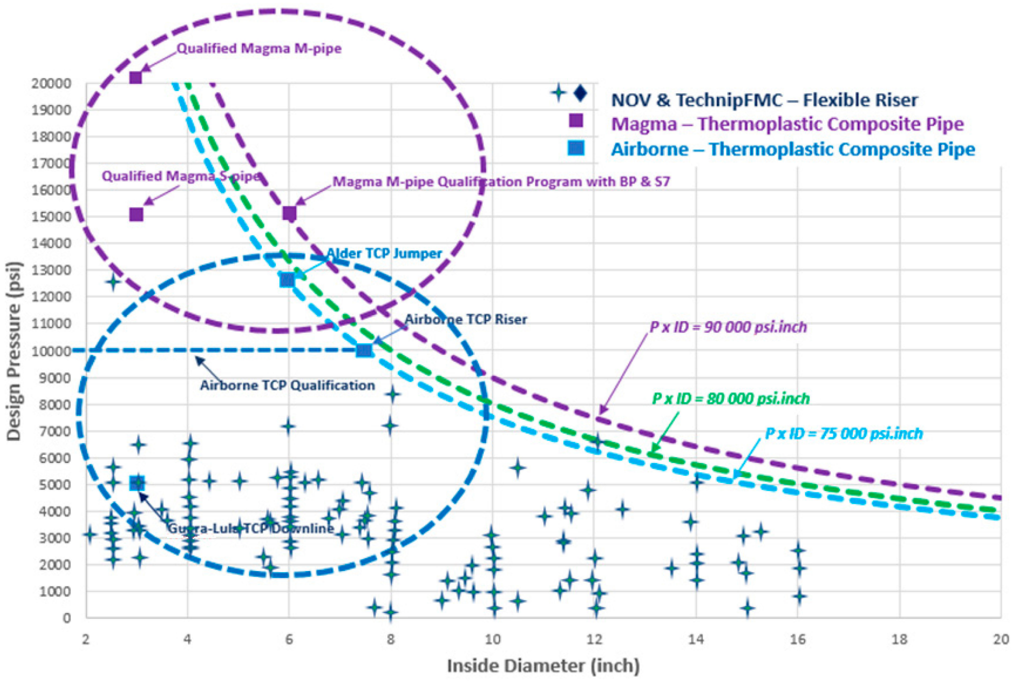

Figure 6. Qualification roadmap of flexible pipes, TCP pipes and composite risers in industry, showing manufacturers including NOV & Technip FMC, Airborne Oil&Gas and Magma Global. (Source: [217,276]; Data extracted from [277]; Courtesy: Leviticus Subsea. Permission to use this image was obtained from Lamacchia D).

TechnipFMC appears to be better positioned for HP projects in the flexible market, whilst NOV appears to be more dedicated to the low-pressure sector. Among these two competitors, GE (formerly Wellstream) flexibles wants to enter the HPHT market with the release of a "hybrid" riser with a composite layer. By using different inner diameter (ID) pipes, the Airborne and Magma Global met offshore market demands for pipes with mid-pressure and mid-temperature applications. These manufactured composite pipes are aiming to reach the same status as the NOV and GE flexible market pipes. Airborne's market limit appears to be PxID = 75,000 psi.inch, based on their expertise and qualifications. The Magma composite pipe is aimed at the HPHT market segment, which is focused on ultra-deep-water applications and is a market that TechnipFMC and GE are pursuing with new research and development as well as the addition of composite layers to lower overall riser weight. Magma's market constraints appear to be at PxID = 90,000 psi.inch, based on their expertise and qualifications [276–280]. With a maximum ID of 7.5 inches, both Magma and Airborne TCP are tailored to small-diameter-ID pipes, which are typical in riser, jumper and downline applications. Larger diameters imply entry into the flowline and pipeline industry, and significant expenditures will be necessary to update real plant capacities, including spooling reels for longer flowlines, in addition to competing not just with flexible pipes but also with inflexible steel pipes. Based on the qualification, the composite riser goes through a validation process once it is designed to guarantee that it can be used on site without endangering the offshore platform. A thorough understanding of the certification methods and risk-based methodologies in DNV-RP-A203 [274] is critical to the success of any high-integrity engineering utilising HPHT.

2.3. Material Characterisation and Metal–Composite Interface (MCI)

An important aspect of the composite riser review is the discussion on the material characterisation and microstructure of composite materials used in developing composite risers, as depicted in Figures 7 and 8. Since the designs of composite risers are based on material designs on their laminas, further investigations on the material strength and effect of the lay-up sequence can be conducted. Each of the laminas (or layers) are made of matrix and fibres, manufactured together, at an orientation angle and with a microstructure, as illustrated in Figure 8a. Different studies have shown that the lay-up sequence has an effect on the strength characteristics of the composite structure [131,257,258]. Another critical aspect of the CPR is the metal–composite interface (MCI). MCI is considered a mechanical attribute of the CPR as well as the thermal conductivity, stiffness and other strength properties of the composite material. The laminate microscopy in Figure 8b shows that the layers of the composite material are structured along different orientations and patterns. In principle, carbon fibres have a higher modulus and strength than glass fibres; however, glass ribbons are more shock-resistant and cost less [237–239]. The resin used is typically chosen based on its ability to absorb oil, water, gas or other fluids. On the other hand, the liner can be made from a thermoplastic extrusion, as in Picard et al. [95], where the liner is the first barrier that the internal fluid encounters, and the thermoplastic material chosen is based on the design requirements. Furthermore, considering the kind of loads faced by a CPR and the variances in material qualities between the orthotropic composite and the isotropic steel, the MCI connection must be cost-effective. Since MCI is a mechanical attribute, it is required that systems that have couplings such as end-fittings undergo HPHT processes for the manufacturing of composite risers, composite tubes, TCP pipes and composite flowlines, depending on the material compositions under high temperatures. Therefore, the MCI is critical, as it provides a secure connection between the composite body and metal couplings at a riser joint's terminations [95,186,187].

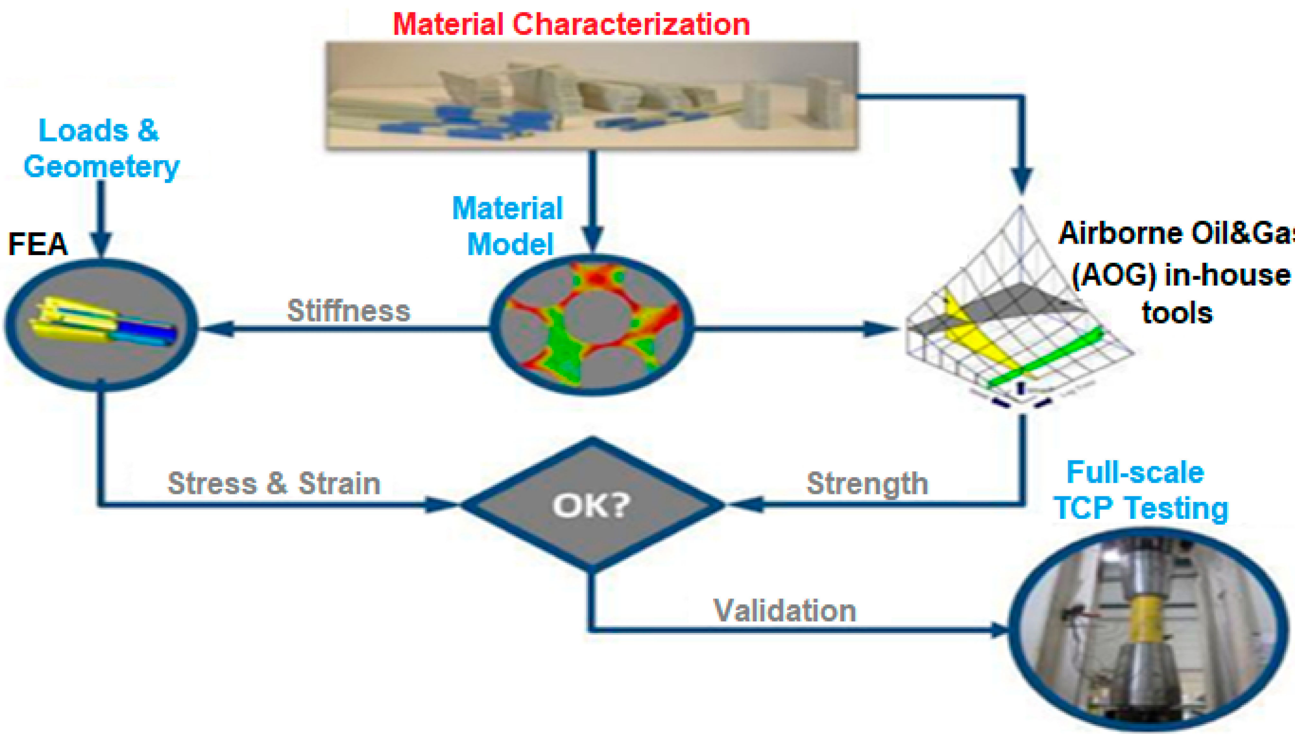

Figure 7. Design procedure for TCP material characterisation. (Courtesy of Airborne Oil&Gas).

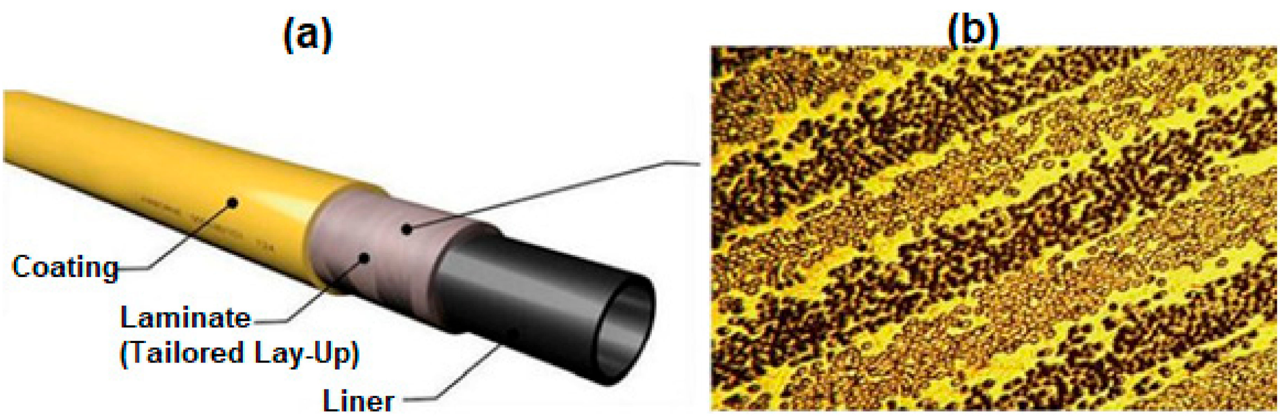

Figure 8. Depiction of (**a**) design concept of TCP pipes and (**b**) laminate microscopy. (Reproduced with permission of Jak Annemarie and Martin van Onna; Courtesy of Airborne Oil&Gas).

2.4. Loading Conditions

The background on marine waves was established by earlier scientists, such as Moskowitz, Pierson, Hasselmann, Kalman, Morison, Bernoulli and Newton [281–285]. They researched the performance of floating structures under various load influencers. These influencers are 'environmental forces', such as ocean waves, external pressures, flows in pipes, flows around cylindrical structures, etc. Hence, the investigation on composite risers using these factors laid the groundwork for hydrodynamics, marine waves and ocean engineering. Figure 9 depicts a typical composite riser with the loadings on it, such as waves and current. Wave forces are regarded as a critical aspect in any riser study since they aid in determining control of top tension, VIV and fatigue prediction [196–199,250,286–297]. Based on industry specifications DNV-RP-F202 [269] and DNV-OS-F201 [270], there are four types of loads on composite risers: accidental loads, environmental loads, functional loads and pressure loads, as tabulated in Table 2.

Furthermore, the pressures exerted by both internal and exterior fluids must be considered while designing composite risers. Under either static or dynamic conditions, the internal fluid pressures, external hydrostatic pressures and the pressures induced by the risers' operating sea depth all contribute to pressure loads. Functional loads, on the other hand, are those that arise as a result of the systems' quiddity, operation and subsistence, with disregard for incidental or environmental impacts. Additionally, it includes the riser's applied top tensions throughout the design and installations, as well as thermal loads. The ocean environment imposes environmental pressures either directly or indirectly, called environmental loads. The loadings that occur by chance and must be analysed against a goal failure probability are called accidental loads. Thermal effects and applied loads cause stress to develop along distinct laminas of the body of the composite tubular structure [278–280].

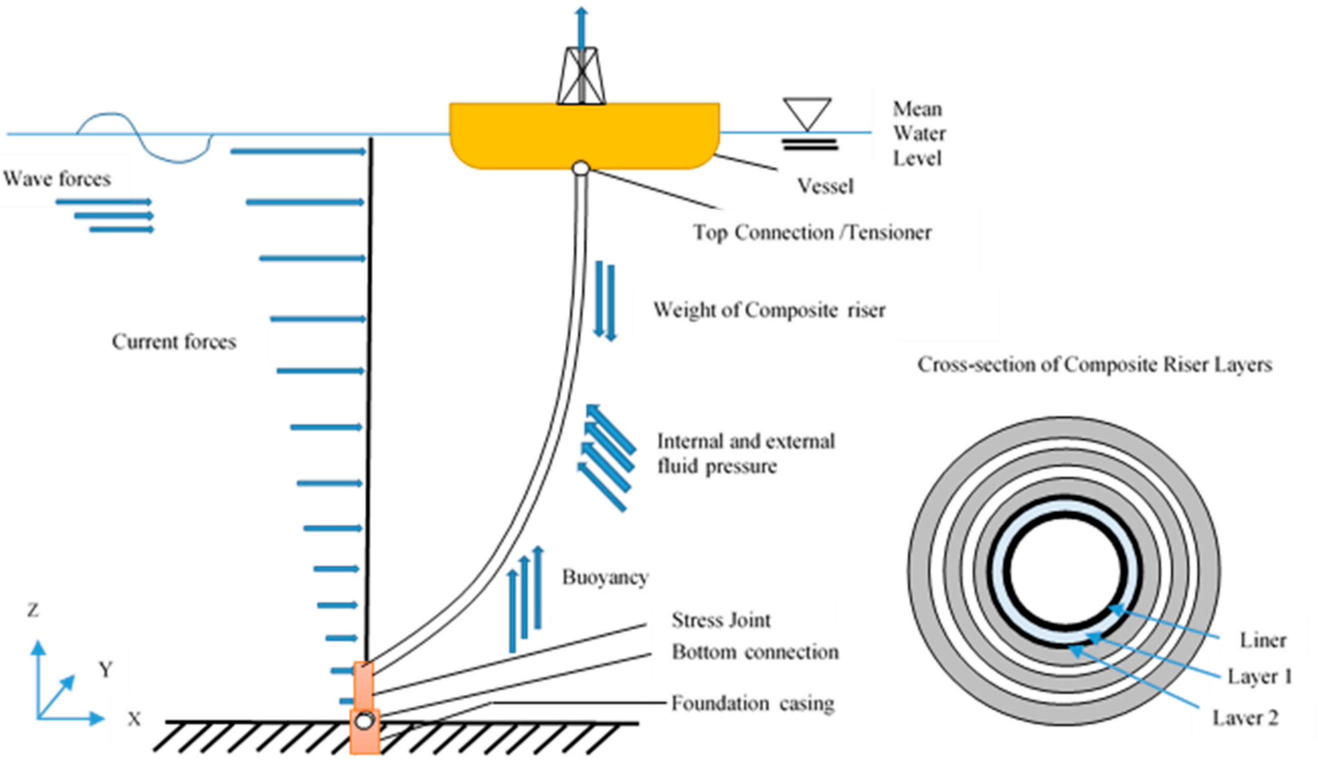

Figure 9. Depiction of composite riser system with loads, layers and cross-sectional cut.

Table 2. Different types of loads (Sources: DNV-OS-F201; 2010 and API RP 2RD).

F-Load or Functional Load	E-Load or Environmental Load	P-Load or Pressure Load	A-Load or Accidental Load
Weight of riser	Floater motions due to currents, waves and wind	Internal fluid pressure (dynamic): global load effects can be generated by both slugs and pressure surges on compliant configurations)	Risk analysis related to support systems, such as loss of mooring line and loss of riser.
Weight of the internal fluid	Vessel motions	Internal fluid pressure (static)	A loosened tensioner in the system
Applied tensions on top-tensioned risers (TTR)	Waves	Internal fluid pressure (hydrostatic)	Fire hazards, explosions and riser collisions.

Table 2. *Cont.*

F-Load or Functional Load	E-Load or Environmental Load	P-Load or Pressure Load	A-Load or Accidental Load
Installation-induced residual loads or prestressing	Current	External hydrostatic pressure	Flow-induced impact between risers
The preloads of connectors	Due to changes in water density, internal waves and other phenomena.	Water levels	Impacts from dropped objects and anchors
Guidance loads and applied displacements, plus support for floater's active positioning system	Dynamic load effects, such as slug flow generated from the fluid pressure (P-Loads)		Naturally occurring environmental issues, such as earthquakes, tsunami, icebergs and hurricanes
Construction loads and loads caused by tools	Icey locations having ice formations or tendency to develop, be slippery or drifts		Failure of lower marine riser package (LMRP)
Soil pressure on buried risers	Seismic effects such as earthquakes (in seismically active regions)		Pressure surge and overpressure of well tubing
Differential settlements	Mean offset including current forces, wind and steady wave drifts		Loss of pressure safety system
Loads from drilling operations	Wave frequency (WF) motion		Seismic effects such as earthquakes (in seismically active regions)
Thermal loads	Low-frequency (LF) motion		Load from anchor, hooks and support systems (hook/snag load)
Inertia			Partial loss of station-keeping capability
Internally run tools			Internal pressure exceeded
Buoyancy of riser (including absorbed water), attachments, fluid contents, anodes, marine growths, buoyancy modules, tubing and coatings.			Risk analysis related to monitoring failure, such as dynamic positioning system (DPS), loss of buoyancy and loss of heave compensating system

2.5. Composite Risers' Layers

Based on the loading conditions discussed in Section 2.4, the stress profiles and safety factor profiles of composite risers can be generated, as given in Figure 10. The industry recommendation in API-RP-2RD [164] stipulates that high-performing composite tubulars have global stiffness as well as stress in various directions, such as fibre, transverse or in-plane shear, as confirmed in Figure 10.

The results profile, using an array of 4 axial layers, 10 off-axis layers and 4 hoop layers with an off-axis orientation of ±53.5°, shows that the titanium liner used worked effectively under the pure tension, collapse and burst loadings of the composite riser modelled using AS4/Epoxy. The local/global design of multi-layered composite risers has been conducted by different research groups as seen in Table 1. The justification for this is that each composite riser design is based on material attributes; thus, the forces on its laminas are subject to its equivalent properties. Each of the laminas (or layers) are made of matrix and fibres, manufactured together, at an orientation angle. A typical composite tubular structure showing its microstructure is depicted in Figure 8b.

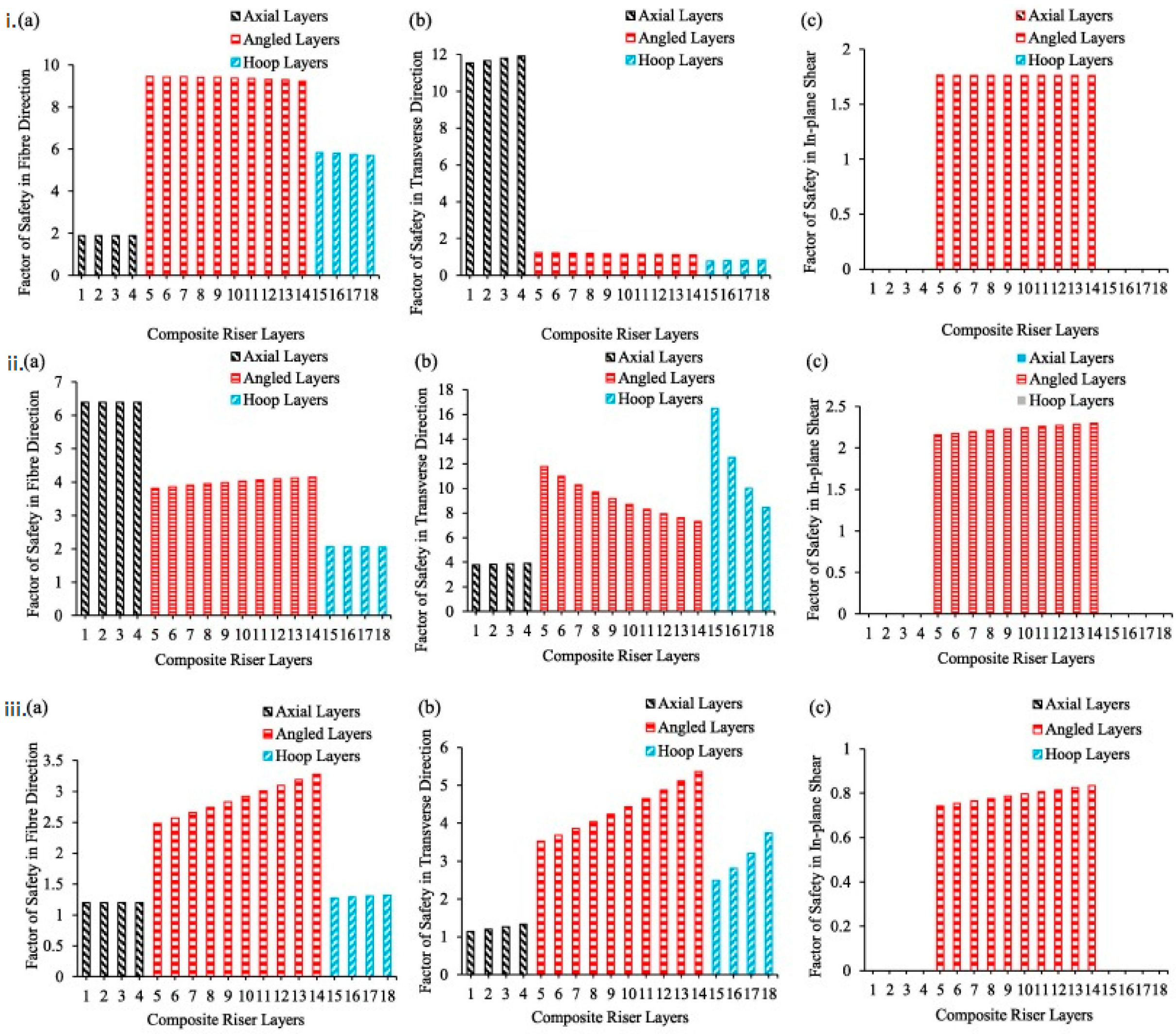

Figure 10. Composite riser with titanium as liners and configured utilising AS4/Epoxy for (**a**) fibre, (**b**) transverse and (**c**) in-plane shear directions, subjected to (**i**) pure tension, (**ii**) collapse loads and (iii) burst loads. The results were obtained from ANSYS ACP's FEM. (Permission to reuse was obtained from Elsevier Publishers, Source: [149]; Published: 15 February 2019; Copyright date: 2018).

2.6. Manufacturing Process

There have been different innovative concepts, designs and patents based on the manufacturing process for composite risers. Salama and Spencer [92] patented a method of manufacturing composite risers with liners aligned horizontally in a production line that is filament-wound. Thomas [229] outlined the procedures for making a composite production riser using filament winding. The traplock MCI, which consists of several grooves to trap a series of composite layers and install them on a mandrel, is often the first manufacturing process [92,160,229]. To make the riser's inner liner, an elastomer layer, such as uncured hydrogenated nitrile butadiene rubber (HNBR), is wrapped around the mandrel. Wilkins [122] described the manufacturing method for a thermoplastic composite pipe made from individual composite tapes that are 10 mm broad, 0.2 mm thick and hundreds of metres long. Several glass and carbon fibres were encapsulated into the thermoplastic matrix to form composite tapes, and adjacent tapes were placed in the same direction to form plies oriented at different directions. These fibres were pressed throughout the entire length of the pipe, and a laser heat source was used to apply thermal each incoming tape, which was then cured chemically and subjected to a thermoplastic welding process to enable a high level of cohesion. This technique could be mechanised, and a robot could be utilised, but it is worth noting that the manufacturing process is critical to the finished laminate's structural strength. A continuous process using a thermoplastic liner and composite-reinforced carbon layers is used to manufacture a composite carbon thermoplastic tube, which is fabricated by winding impregnated fibre ribbons around the thermoplastic liner at specific angles, with the thermo-fusion controlled to ensure proper placement on the liner. The CPR manufacturing process, according to Baldwin et al. [75,76], comprises an examination of fibre stress rupture data, which aids in forecasting the composite structure's average stress rupture life, desired service life and reliability. During the manufacturing process, special attention is paid to the end-fittings to guarantee that the connections between the pipe lengths, anchoring and MCI are appropriately blended. It is critical to alternate the hoop and axial reinforcements throughout the composite riser production process, as this influences the mechanical properties of the composite riser. Figure 11 shows an example of composite layers for the composite riser pipe showing lay-up patterns. It is worth noting that the manufacturing method that industry leaders such as Airborne Oil&Gas employ relies on some complexities in the capacity to create long lengths of continuous pipe; meanwhile, the production technology has been certified by DNV for the creation of qualified products. The composite polymers used in Airborne include polyethylene (PE), polypropylene (PP), polyamide (PA), polyvinylidene difluoride (PVDF) and polyether ether ketone (PEEK). According to Osborne [115], when the company creates a PP composite pipe, it starts with a PP liner, then melt-fuses glass/PP tapes onto the PP liner and melt-fuses a PP jacket on the exterior. According to the report, Airborne's technology produces a strong and stiff pipe comprising a single polymer and a single-fibre system. It further reported that it was the world's first manufacturer to succeed in producing a continuous solid thermoplastic composite pipe, which differs from reinforced thermoplastic pipe (RTP) in that RTP is frequently unbonded, requiring loose fibre layers or tapes to be wound around the liner, before Magma Global joined in similar manufacturing technique around 2015. RTP is unable to sustain external pressure and cannot be used in deep waters offshore. The pipe from Airborne is made of a thermoplastic compound and has three parts: a jacket, a composite and a liner, as shown in Figure 5. A thermoplastic is used to make the lining. Strength and stiffness are provided by glass or carbon fibres. The fully bonded flexible pipe is melt-fused during production; the pipe has a single solid wall made of glass fibres, E-glass or/and S-glass. Carbon fibres, but not aramid fibres, are the other material utilised, as the latter do not perform well under compression (So, a pipe made from aramid cannot handle high external pressure.). The tape fibres are impregnated into the plastic liner using the same plastic as the liner. As a result, the tapes are looped around the liner and melt-fused to it, with the tape then being melt-fused to the underlying tape and continued [115].

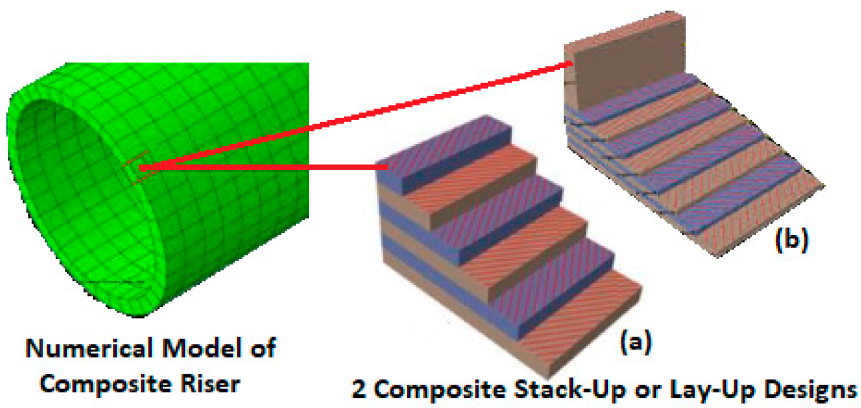

Figure 11. Typical composite riser structure showing (**a**) tubular structure and (**b**) the layers with two different lay-up sequences.

2.7. End-Fitting

In summary, these studies on the end-fittings will enable the designer to understand the behaviour at the joints and connections. Additionally, the pressure exerted at the joints of the composite risers creates some stress at these end-fittings. Lincoln Composites reported numerical and experimental assessments of a composite riser end-fitting joint using a CFRP tube and steel pipe (X80), which included the metal composite interface (MCI) for autofrettage prestressing and a factory acceptance test (FAT) [109,110]. The FEA showed the regions of high stresses on the neck of the end-fitting, mostly on the grooves, as shown in Figure 12. It was conducted by first setting up the end-fitting, then axially stretching the steel pipe. Secondly, a design pressure that exceeded its yield strength was exerted during a burst or internal pressure test. Next, the pressure was relieved and reapplied at a reduced scale. The results were recorded, and finally the pressure was released to relieve the system.

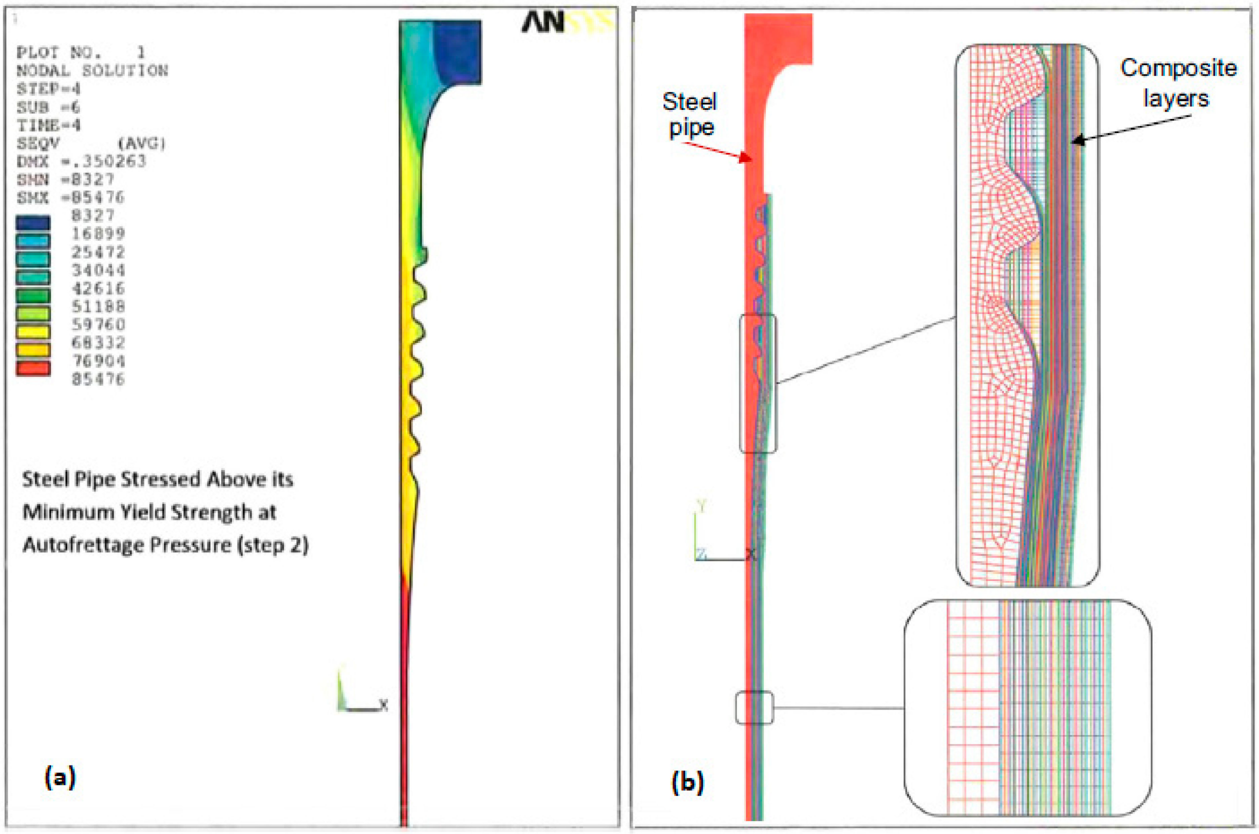

Figure 12. Finite element model of composite riser end-fitting joint in ANSYS, showing (**a**) Compression stress in the steel pipe, and (**b**) the local design for the riser joint model (Permission to reuse was obtained from (i) OTC's OnePetro Publisher and (ii) Elsevier Publishers; Source: [109,110,160]. Published: (i) 06 May 2013; Copyright date: 2013; (ii) 22 December 2015; Copyright date: 2016).

In this review, three end-fittings are considered: the traplock end-fitting, Magma end-fitting and Airborne end-fitting. Baldwin et al. [76] was the first recorded patent with traplock end-fitting device. For thermoset composite risers, a traplock end-fitting was created. A number of grooves are carved into the two ends of the mandrel in this design, allowing load transmission between the composite laminate and the metallic connector ends. The displacement vs. force profile of a traplock end-fitting with double the number of grooves is shown in Figure 13a. Some comparative studies on end fitting designs are carried out in literature [187]. These are based on different inventions and patents on composite risers which are currently been applied in the industry [74,76,92,188].

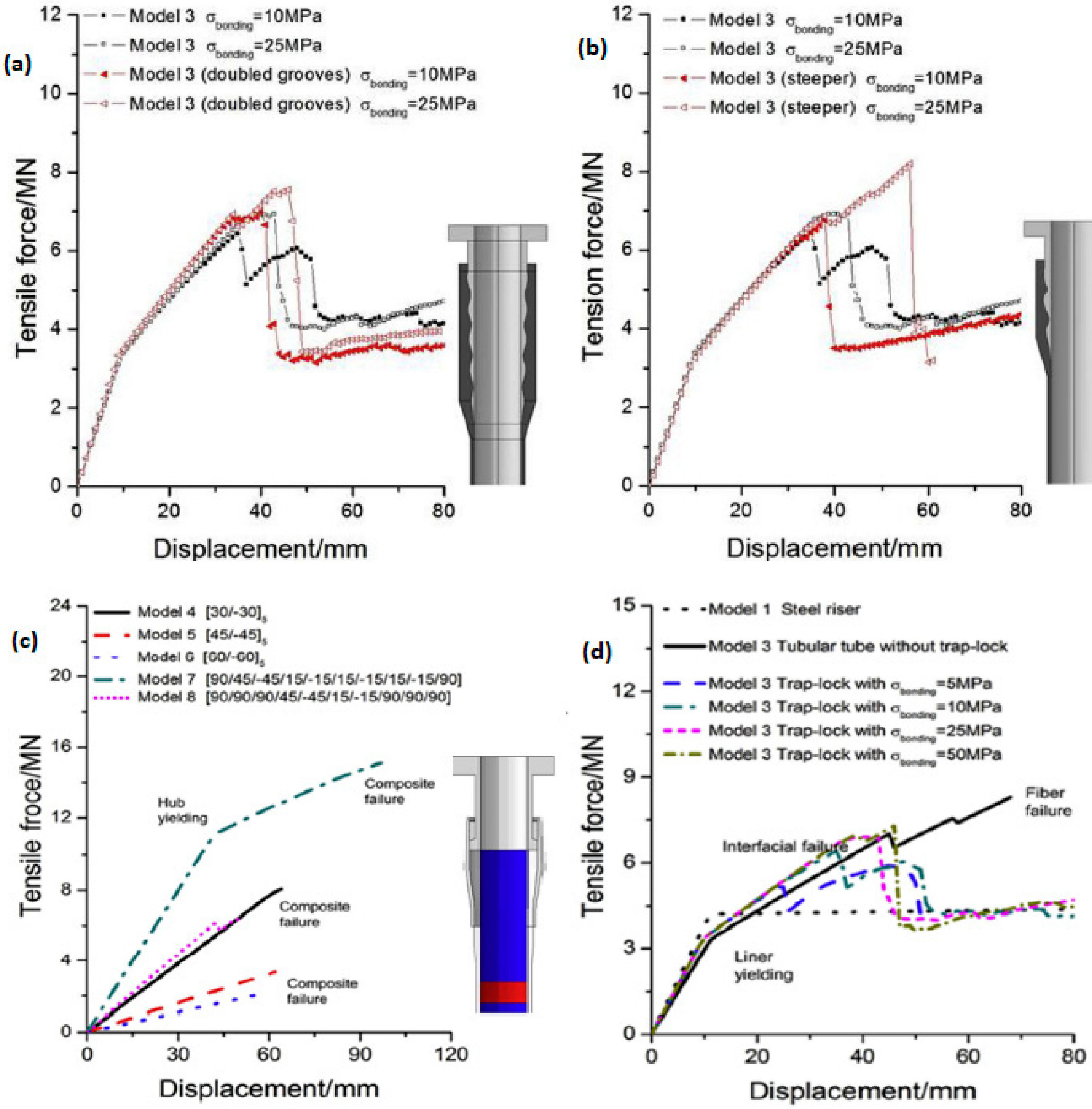

Figure 13. Results of displacement vs. force profiles for different models with load transfer mechanism of traplock and Magma end-fitting models, to present the failure profiles from tension loads on the body of the composite riser pipe. It shows the displacement-force curves of (**a**) trap-lock end fittings with doubled number of grooves, (**b**) trap-lock end fittings with steeper grooves, (**c**) Magma end fitting model with different composite laminates, and (**d**) trap-lock end fitting with steel riser and other composite risers. (Permission to reuse was obtained from Elsevier Publishers, Source: [187]; Published: 4 June 2018; Copyright date: 2018).

As shown in Figure 13a,b, the load transmission was accomplished by a combination of mechanical compression force and adhesive bonding force. Stress concentration and possible debonding between the liner and composite laminate can be caused by the grooves at both ends. The valley of the grooves with thinner walls may experience yielding, necking and subsequent failure as a result of such debonding. To avoid this, the wall thickness at the groove region was purposefully increased from the middle to both ends [74–76,187]. As a result of the thicker wall at the MCI region, the axial stiffness increased slightly, as demonstrated by the force–displacement response. However, it had little effect on the ultimate tensile load (UTL), which is mostly governed by interfacial strength, which is unaffected by extra grooves. The results of another end-fitting are shown in Figure 13b, where the groove interfaces were steeper and saw-toothed, as suggested by Baldwin. This adjustment had no effect on the response's axial stiffness, but it did allow for a higher UTL. The basic lengths of all grooves remained unchanged in all circumstances, suggesting that the end-fitting section length in the cases depicted in Figure 13a is double that of the length shown in Figure 13b, whereas the section length in Figure 13b is equals that shown in Figure 13d, as seen in the cumulative results. For the Magma end-fitting shown in Figure 13c, it can be seen that slope—either gentle or steep—and frictional coefficients had an effect on the strength of the end-fitting.

The qualification of the Magma m-pipe design that incorporates a fibre and matrix of Victrex PEEK to make composite laminates was reported in literature [121,122,126]. It was demonstrated by applying an axial load of 23.9 MPa as an operational pressure load, 42.75 MPa as a test pressure load and an internal pressure load of 38.3 MPa. In an earlier investigation on Magma end-fitting, Hatton [119] avowed carbon fibre/PEEK pipes to be a potential enabler for offshore applications. The study covered the end-fitting design, which enables further manufacturing activity by serving as a stable structural interface with the steel end-fitting. As comparatively shown in Figure 13, each end-fitting has unique features that make them useful for special applications, as seen in the Airborne end-fitting in Figure 14a. The Magma end-fitting is presented in Figure 14b.

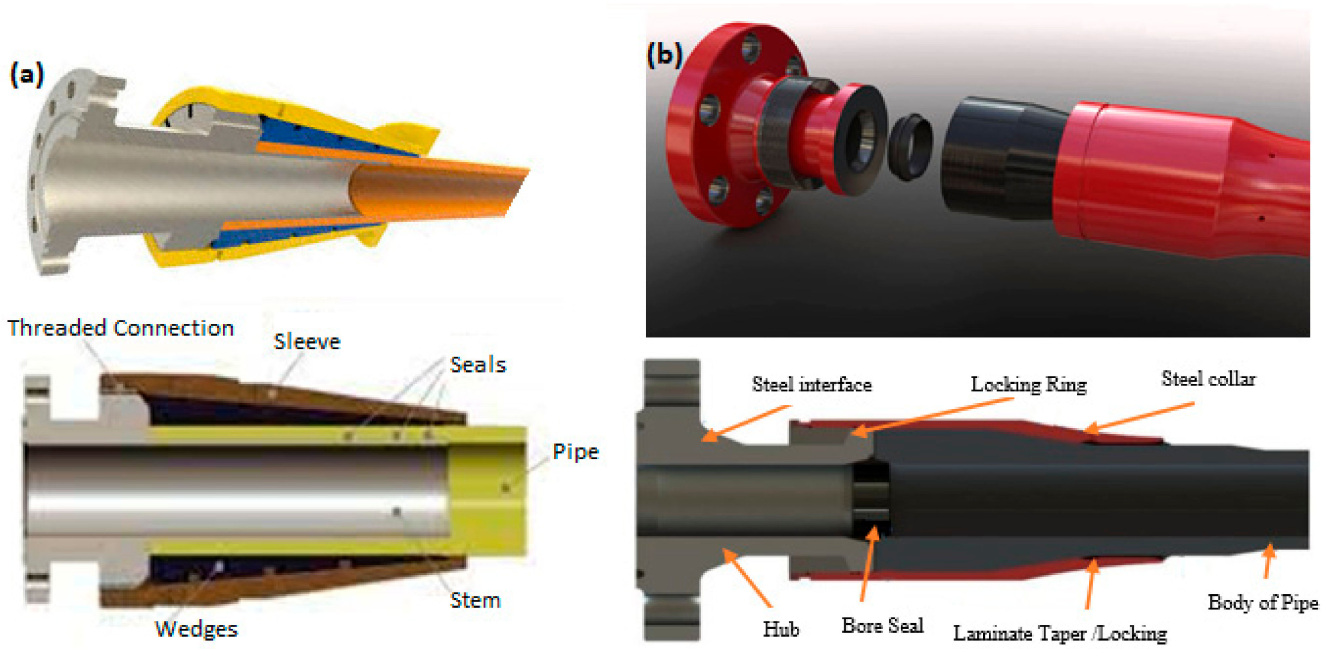

Figure 14. End-fitting designs for (**a**) Airborne end-fitting and (**b**) Magma end-fitting. (Permission to reuse was obtained by the industry designers—Airborne Oil and Gas for Image (**a**) and Magma Global for Image (**b**)).

3. Mechanical Behaviour

In this section, the mechanical behaviour is discussed and reviewed.

3.1. Strength Behaviour

A comprehensive analysis of the strength behaviour and economic consideration of composite risers is carried out here. Economic assessments from literature show that composite risers are comparatively more expensive than steel risers [55,196–199,217,246]. It has also been observed that different CPR models have been developed to ascertain the strength of composite risers, in comparison to steel risers. Table 3 shows various mechanical behaviours and loads that can be applied in a composite riser model when analysing the mechanical behaviour of composite risers. Steel is a universal benchmark material in riser systems because it has tested track records, especially regarding failure behaviour and strength characteristics. This is not the case with composites. Steel also has more design codes than composite materials; thus, it differs from composite materials used for CPR designs, as seen in their physical properties, as shown in Table 4. Additionally, in comparison to composites, steel is heavy, requires high maintenance and fabrication, has a high installation but low material cost and must be coated because it is corrosive [135,235,293–295]. Comparisons based on the mechanical, chemical and physical properties of composites against steel and wood have shown that composites to have excellent behaviour in coastal environments, as opposed to mild steel [295–300].

Table 3. Models for analysis of mechanical behaviour of composite risers.

Type of Model	Problems to Be Solved	Loads to Check for
Composite risers	Global analysis and local analyses	Load distribution on riser ends
Compound infinite anisotropic cylinder	Stress and strength analysis, selection of layer thicknesses and technological parameters	Dead weight, internal pressure, external pressure, residual stresses from force winding and thermal shrinkages
Compound semi-infinite cylinder	Stress concentration and length of boundary effect zone	Load distribution effect on riser ends
Cylindrical sections of different lay-ups on axial coordinate	Selection of reinforcement scheme at different depths of sections	Load variation along axial coordinate
Cylindrical section with lay-up varying in wall thickness	Optimisation of reinforcement scheme of riser sections	Nonuniformity of stress fields on wall thickness
Extensible weighted thread	Estimation of axial strength, effect of extensibility of riser axis on its deflection	Dead weight and flow-past
Flexible rod in linear statement	Calculation of riser deflection and stresses	Flow-past, reactive forces and moments
Flexible rod in nonlinear statement	Stresses, deflection, required top tension at longitudinal-transverse bending and buckling	Dead weight, flow-past, top end tension, reactive forces and moments
Laminated cylindrical tube	Displacements and stresses	Bending loads, torsion, tensile loads, external pressure, and internal pressure.
Multilayered cylindrical shell	Stress, strain and strength analysis	Effect of asymmetric loading (flow-past, concentrated loads)
Repaired cracks in composite pipes	Fracture using stress intensity factor (SIF)	Load distribution
Quasilinear 3D anisotropic elastic cylinder	Refined calculation of stresses	Synergetic effect of different loads

Table 4. Material attributes of composite risers compared to other materials.

Property	Specific Gravity	Young's Modulus (GPa)	Poisson Ratio, v	Density (kg/m^3)
Composite Riser	1.68	(depends)	0.28	1680
Steel	7.8	200	0.30	7850
Titanium	4.43	113.8	0.342	4430
Aluminium	2.78	68.9	0.33	2780
PEEK	1.32	5.15	0.40	1300
P75/PEEK	1.77	33	0.30	1773
P75/Epoxy	1.78	31	0.29	1776
Sea Water	1.0	2.15	0.5	1030
AS4-PEEK	1.56	66	0.28	1561
AS4-Epoxy	1.53	49	0.32	1530

To evaluate the strength of marine risers, effective tension profiles are usually used [11,24–27,98,137–142,149–153]. Details of similar effective tension profiles on marine hose risers are available in earlier studies [48–53]. In the comparative study by Kim and Ochoa [98–104], the findings show that the composite riser had a tension factor of 1.3 with a top tension of 1418 KN, whereas a comparable steel riser requires 3822 KN. Here, the cumulative weight of the submerged weight of the riser and the internal fluids in the riser was used because the effective weight of any riser is very important [98]. An earlier NIST study [99] recommended the replacement of steel joints with composite riser joints; however, the findings of Dikdogmus [43], avow the challenge of replacing steel with composite materials, as the riser design must focus on the variety of loadings and water depths. Saleh [199] opined that composite risers are more expensive than steel risers, but they also have the lowest life cycle cost as composite materials require less maintenance, unlike steel materials. It is noteworthy to add that the composite riser pipe costs about three times the cost of an equivalent steel riser pipe. However, the replacement of the steel pipe with a composite pipe improves the life on site by a factor of more than 100 times. As regards the performance of the riser, it improved significantly due to the fatigue characteristics of the composites and the absence of welds along the riser leg. Another comparison conducted on CPR models by Brown [246] showed that there is high potential for the utilisation of composite risers, as it shows good results from utilisation on flowlines and TCP pipes, as shown in Figure 15. Studies on the use of titanium alloys in CPRs for FPSO, TLP, and Truss SPAR found that titanium alloys have high mechanical attributes suitable for Composite risers [211,212,295–306] but the configurations, fatigue, reliability, large-scale experiments and cost should also be considered [156,157,161,247,303,306–317]. A bibliographical list of the comparative studies on composite risers is in Table 5.

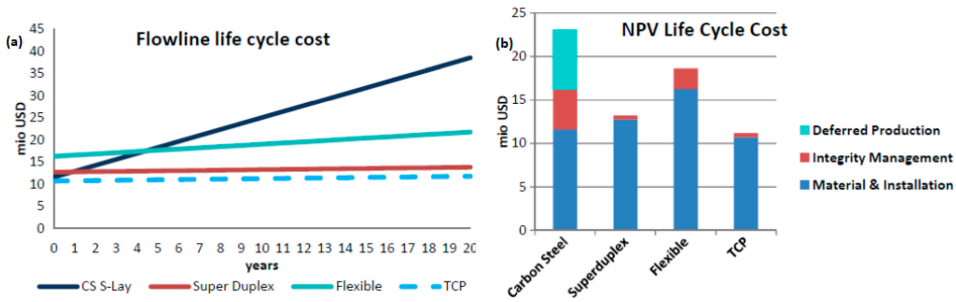

Figure 15. Potential of marine composites in TCP flowlines and composite risers, showing (**a**) flowline life cycle cost, and (**b**) NPV life cycle cost (Courtesy of 2H Offshore, Source: [247]).

Table 5. Bibliographical list of comparative studies on steel risers and composite risers.

Authors	Title	Highlight
Gibson A.G. [306]	Composites for Offshore Applications	Compared steel, protruded FRP against steel and wood
Hopkins P. et al. [196]	Composite Pipe Set to Enable Riser Technology in Deeper Water	Compared both steel and composite riser performances and riser fatigue
Cheldi T. et al. [4]	Use of spoolable reinforced TCP pipes for oil and water transportation	Spoolable reinforced TCP pipes, material design
Toh W. et al. [187]	A comprehensive study on composite risers: Material solution, local end fitting design and global response	End-fitting design for composite risers and global design with VIV responses
Hopkins P. et al. [197]	Composite riser study confirms weight, fatigue benefits compared with steel	Compared the composite risers and steel riser with material attributes
OGJ [211]	Composite riser technology advances to field applications	Compared the composite risers and steel riser with material attributes
Pham D.C. et al. [160]	A review on design, manufacture and mechanics of composite risers	Comparative assessment of the literature
Amaechi C.V. et al. [149]	Composite Risers for Deep Waters Using a Numerical Modelling Approach	Numerically compared composite riser models, compared different liners
Ward E.G. et al. [101]	A Comparative Risk Analysis of Composite and Steel Production Risers	Comparison assessment, local design, global riser analysis and risk analysis for both steel and composite risers.
Pham D.C. et al. [159]	Composite riser design and development—a review	Comparative assessment of the literature
Saleh P. [199]	The benefits if composite materials in deepwater riser applications	Benefits of composites in developing composite risers
Brown T. [246]	The impact of composites on future deepwater riser configurations	Configurations for composite risers, with fatigue of steel and composite risers
Lamacchia D. [217], Lamacchia D. et al. [276],	Thermoplastic Composite Pipe (TCP) Offshore Market 101	Compared MagmaGlobal and Airborne Oil&Gas TCP pipes for composite risers
Saad et al. [55]	Application of composites to deepwater top tensioned riser systems	Economic aspects of composite risers on SPAR and TLP
Mintzas A. et al. [134]	An integrated approach to the design of high performance carbon fibre reinforced risers—from micro to macro scale	Combined bend–burst, burst and compressive tests
Amaechi et al. [153]	Local and Global Design of Composite Risers on Truss SPAR Platform in Deep waters	Comparative assessment of composite risers; local and global design
Wang et al. [141]	Tailored design of top-tensioned composite risers for deep-water applications using three different approaches	Numerically compared composite riser models, compared 3 different approaches
Gibson A.G. [80]	The cost effective use of fiber reinforced composites offshore	Compared the composite risers and steel riser with material attributes
Andersen W.F. et al. [71]	Full-Scale Testing of Prototype Composite Drilling Riser Joints-Interim Report	Full-scale testing on composite riser
Wang et al. [142]	Global design and analysis of deep sea FRP composite risers under combined environmental loads	Numerically compared composite riser models, global and local design
Kim W.K. [98]	Composite production riser assessment	Compared steel and composite risers, local and global design,
Gibson A.G. et al. [82]	Non-metallic pipe systems for use in oil and gas.	Application of composite pipes

3.2. Global Performance

The industry specification DNV-OS-F201 [270] stipulates that reasonable probability must be considered for the marine riser during its design, manufacture, fabrication, operation and maintenance so that it can stay ready until its usage. Taking into account its service life and cost, it should remain suitable for the task for which it was designed.

Furthermore, the riser should be able to withstand all predicted loads and related forces that may be experienced over its service lifetime, as well as have suitable durability in proportion to maintenance costs; thus, it should be built with the right degree of reliability. An illustration of a global analysis model is shown in Figure 16, which illustrates the marine risers and the catenary mooring lines. The global response, structure's geometry, structural integrity, stiffness, trans-sectional properties, material attributes, sea-wave behaviour, supporting methods and prices (or economic savings) are all important factors to consider while developing the composite riser structure.

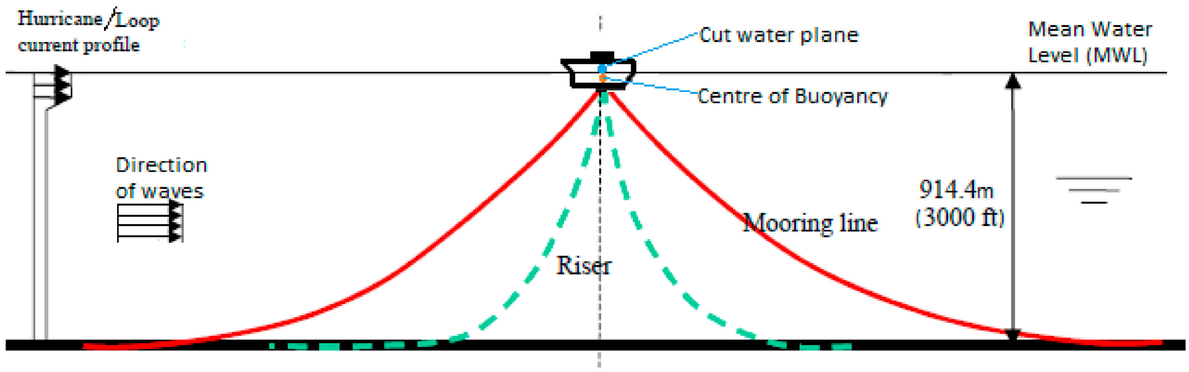

Figure 16. Schematic showing risers and mooring lines on a floating platform.

Hopkins et al. [197] comparatively studied the main criteria for designing composite risers and steel marine risers, operating at a water depth of 2000 m on a conventional single-leg hybrid riser (SLHR) with a steel riser leg. The authors concluded that composite systems have been tested and can be used in offshore risers, as they are further developed using newer riser applications and configurations. In the comparative assessment between composite risers and steel risers by Brown [246], the effect of configuration was also opined as a factor, as there is a shift in the tension from the hang-off when comparing different fluid contents, as shown in Figure 17a. When the riser configuration was ballasted to change the configuration, as depicted in Figure 17b, it added some flexibility and it decoupled the vessel motion and changed the tension distribution, as shown in Figure 17c. This confirms that an increment in the ballasted weight will reduce the bending and angle of the hang-off, while it increases the hang-off loads, based on riser configurations. Roberts & Hatton [126] presented a lightweight design that reduces both drag and weight loadings. This results in a much-enhanced riser response, with all essential factors, such as the foundation loads, buoyancy module size, installation loads, etc., being decreased drastically. This confirms that when designing the model's setup, the host vessel's motion characteristics, specific environmental data, numbers on the field layouts, layout array for the moorings, number of risers required, deck loads on the platform, likelihood of interference, hang-off location, access to a host vessel and the depth of the sea must all be considered, as well as the fact that it is a composite riser. However, debonding would increase the load carried by the matrix; hence, the fibre–matrix interface is critical in achieving a suitable composite structure. Indeed, the debonding phenomenon allows the composite to bear a further strain after the failure of the fibre since the matrix starts to carry the stress around the broken fibres, but after that, the composite is considered to no longer be in working condition. In addition, in comprehensive investigations on the composite material makeup and the stack-up composition of the layers, it is very important to consider the configuration of the composite structure (like TCP flowline or composite riser), as it might be aligned vertically or in S-shape (such as steep-S, lazy-S, lazy wave, etc.), which may vary in wave form, with respect to riser length, the sea bed type and the sea depth [23–25,301–310]. Application of composites have also been extended to marine hoses as marine bonded composite hoses (MBCH) [14,15,154,155,227]. In the global analysis by Amaechi et al. [48–53], the strength of marine bonded hoses was assessed numerically using a coupled model in ANSYS AQWA and Orcaflex, with the hydrodynamic loads from the CALM buoy structure on the riser model (submarine hoses), which was designed in a Chinese lantern configuration. However, there is presently no publicly available literature covering such application on composite risers. Current applications of global design are based on the loadings or deployment as top-tensioned risers [140–142,152,153,156,157]. For fully developed composite risers, this configuration may not be as effective as vertical configurations on a Truss SPAR [152,153], and TLP [140–142,296]. Aside from these, there are other proposed configurations for the hybrid flexible composite riser model and a composite riser using a buoyancy tank, similar to the single-leg hybrid riser (SLHR).

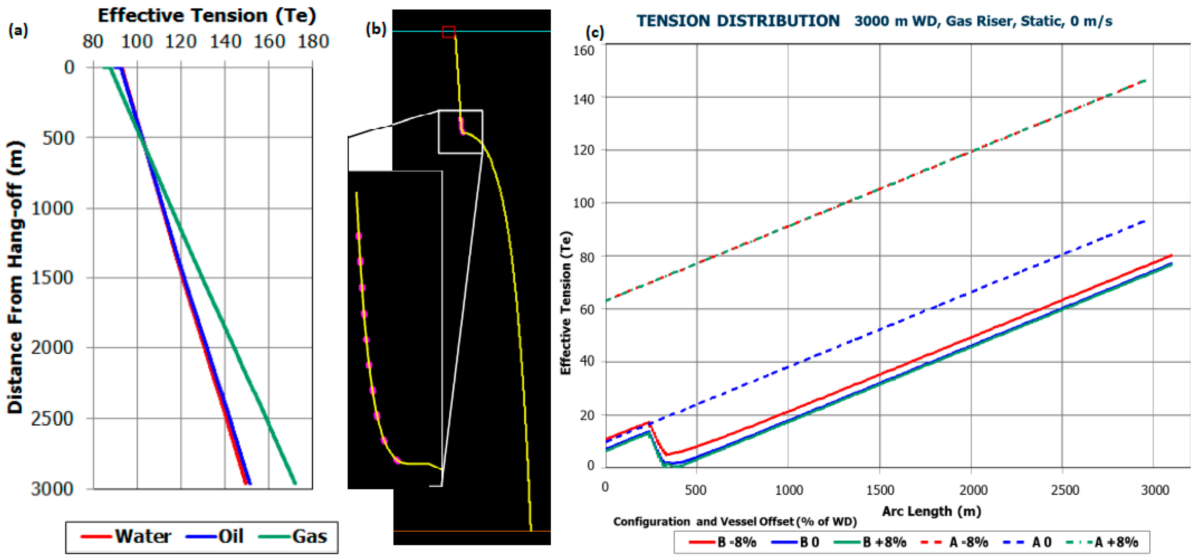

Figure 17. Tension profiles (**a**) during hang-off for different fluids, (**b**) the hang-off configuration when ballasted and (**c**) tension profile when ballasted (Courtesy of 2H Offshore, Source: [247]).

3.3. Vortex-Induced Vibration (VIV)

The importance of vibration control with different methods for offshore structures has been presented in the literature [37]. The flexibility of modern polymer–matrix composites allows for true integrated sections. The thickness, on the other hand, might be adjusted to obtain the required fibre mix with commensurate fluctuation in the stresses. The stack-up of the composite laminate and orientation is critical to the composite tubular's strength, as discussed in Section 2.5. Looking at the mechanical behaviour of composite risers, VIVs on CPRs have been increasingly investigated experimentally with numerical analysis. In an earlier investigation by Omar et al. [200], although the study did not consider a detailed riser analysis, it compared composite TTRs and steel risers, considering dynamic response characteristics in ABAQUS and taking into account the damage rate of each configuration, top tension requirement, VIV amplitudes and VIV-induced local stress. In another study, Wang et al. [143] presented a comparative assessment of the VIV of composite risers using computational fluid dynamics (CFD) in both 2D and 3D models. The vorticity profiles are shown in Figure 18. The natural frequencies and reduced velocities of nine cases were investigated and further examined in [144–146], who presented mode shapes for the FRP composite risers with distinctively different responses to those of steel risers. The study concluded that at 2.13 m/s, the VIV responses of all three risers were almost 30 times those at 0.36 m/s and 3 times those at 1.22 m/s. At 2.13 m/s, the VIV responses of global stresses for all three risers were nearly ten times higher than at 0.36 m/s and three times higher than at 1.22 m/s. "Lock-in" for the steel riser (riser 1) and optimised FRP composite riser (riser 2) only occurred in the 100-year loop current condition at 2.13 m/s. The comparisons reveal that composite risers have better dynamic response characteristics than steel risers.

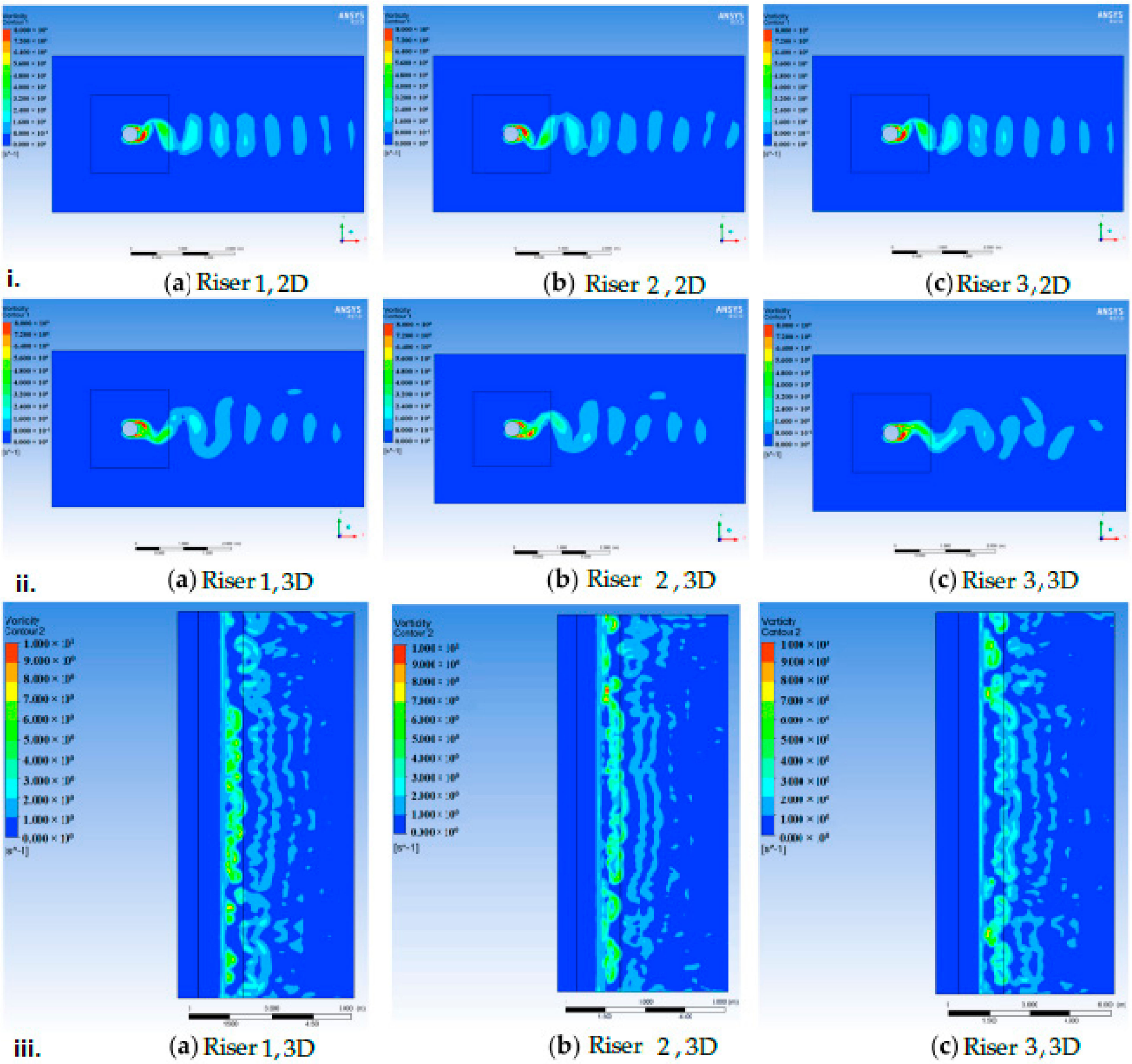

Figure 18. Profile of vorticity in 2D and 3D models for: Riser 1; Riser 2; and Riser 3. Here, (**ia**–**ic**) presents the vorticities for Risers 1, 2 and 3 using 2D models; (**iia**–**iic**) illustrates the vorticities for Risers 1, 2 and 3 with 3D models; and (**iiia**–**iiic**) presents vorticity profile in 3D models for (a) Riser 1; (b) Riser 2; and (c) Riser 3. (Permission to reuse was obtained from MDPI and author 5-C.W., Source: [143]; Published: 27 April 2018; Copyright date: 2018).

Similarly, the earlier study [200] revealed that the maximum VIV stress of a composite riser was substantially lower than that of a steel riser, demonstrating that composite risers have longer fatigue lifetimes. Likewise, Kim [98], Sun et al. [255], Tan et al. [226] and Toh et al. [187] used different techniques like finite element method (FEM) to conduct thorough analyses on both local and global scales on composite and steel risers, finding higher safety factors for composite risers. However, the composite riser models without any VIV suppression exhibited mild fatigue damage. Hence, adding strakes and buoyancy modules to a composite riser could improve VIV responses [203,226,293].

3.4. Dynamic Behaviour

In this section, some studies on dynamic loading on risers are briefly examined. The riser tensioner system for a buoyancy tank was studied by Kang, Z. et al. [311]. Dynamic models were used to assess computing fatigue damage using the fatigue model and compared to benchmarked criteria for maximum permitted stresses coupled with the RAO data [23,162–166]. The dynamic behaviour of risers in seismic designs is different because seismic conditions must be taken into account in the riser design in order to control seismic responses because resonance occurs when the frequency falls within the range of earthquake wave frequencies, causing higher seismic stresses in the riser [312]. Since damping is already included in the response model, the contribution of hydrodynamic damping (which is proportional to the water velocity and compensates for the damping impact of the surrounding water) in VIV within the lock-in region is set to zero (0). According to Sanaati et al. [288], higher applied tensions that result in lower vibration amplitudes can greatly improve the hydrodynamic lift force and are an effective instrument for the active management of riser statics and dynamics. The hydrodynamic interaction is a system-dependent issue in load effect assessments connected to riser interference evaluations (see DNV-RP-F203 standard [313]). Some researchers performed reviews on the modelling and analysis techniques for hydrodynamic assessment of flexible risers to represent the static analysis, frequency domain dynamic analysis and time domain dynamic analysis for a flexible riser, as well as the internal and external pressure effects and information on fluid flows [206–209].

API-RP-2RD [314] examined several riser configurations based on the following criteria: structural integration (integral vs. nonintegral risers), means of support (top-tensioned with tensioners or hard mountings vs. concentrated or distributed buoyancy), structural rigidity (metal vs. flexible risers) and continuity (sectionally jointed vs. continuous tube). Conversely, static analysis was used to determine the riser's configuration; it should be noted that riser configuration design was carried out in accordance with production needs and site-specific environmental circumstances [313–315].

3.5. Experimental Tests

Recent developments have involved JIPs such as Cost Effective Riser Thermoplastic Composite Riser JIP in 2009 and Safe and Cost Effective operation of Flexible Pipes in 2011–2013 [80,306,316,317]. As presented in Table 1, different experiments on composite risers have been conducted to achieve qualification and advances made. In principle, experiments are required for both local and global design, as well as validation of results, because they reveal the test techniques and materials utilised [317–326]. The highlight of related experimental studies on composite risers, composite tubes, cylinders and shell structures are indicated in Table 6. Since marine risers are tubular structures with varied segments, the experimental tests on composite risers were conducted at microscale levels (on composite materials) [257–259] and at macroscale levels (on composite risers with composite tubes) [47,80,307,308], which are benchmarked against those of marine steel risers, such as steel catenary risers [35,286]. It is also crucial to test the failure in risers, as research on carbon-fibre-reinforced composite risers have revealed failure mechanisms [59–63] linked to various loading scenarios [131,134,187,195]. Previous experimental studies on composite risers were based on scale-dependent methods of analysis, as tabulated in Table 6. Presently, the scale tends to shift more towards small-scale methods. The tests conducted include failure tests, fatigue, collapse and burst pressures [148–152]. There are limitations to full-scale testing, as can be seen in the size of composite risers as shown in Figure 19. The first full-scale model examination was an external pressure test to determine the collapse pressure capabilities of the riser main body construction. Andersen et al. [70–72] developed a specially configured test fixture that used a circumferential compressive load rather than just end loads on the specimen during the test since that was designed to meet the standards for a 1500-pound riser's main body structure.

Table 6. Experimental tests on composite risers with the scale of the testing.

Reference	Highlights and Test Modes	Specimen Type	Program/Test Scale
Sparks et al. [68]	Attributes of composite risers on concrete TLP, collapse pressure test, fatigue test	Composite riser	Full-scale and small-scale
Andersen et al. [71]	Burst, and tension tests	Composite drilling riser joint	Full-scale
Gibson [81]	Flexure, tension, fire, durability, blast, impact test, axisymmetric burst, marine composite application, fatigue test	Fibre-reinforced composite pipes and coupons	Full-scale and Small-scale
Picard D. et al. [95]	Tensile test, manufacture of TCP pipe	Composite tube	Large-scale
Ramirez and Engelhardt [96,97]	Collapse pressure test, buckling	Composite tube	Full-scale
Alexander et al. [105]	Burst, bending cycles, impact/drop tests	Composite tube	Full-scale
Cederberg et al. [109,110]	Burst, collapse and impact tests	Composite drilling riser	Full-scale
Mintzas et al. [134]	Tensile test, micro-scale test	Carbon fibre repaired riser	Small-scale
Chen et al. [186]	Burst, and tension tests	Composite riser end fitting	Small-scale
Pham et al. [161]	Bending under transverse loads	Composite pipe and coupons	Full-scale
Sobrinho et al. [224]	Thermal and Mechanical tests		
Ye et al. [257,258]	Tensile test, SEM and CT tests	Glass fibre composite/epoxy	Small-scale
Ellyin et al. [262]	Flexure test, tension test	Composite pipes and coupons	Small-scale
Grant and Bradley [280]	Flexure test, tension test	Composite pipes and coupons	Small-scale
Huang et al. [307,308]	Tensile and fatigue tests	Carbon fibre composite pipe and coupons	Large-scale
Alexander and Ochoa [327]	Burst, tension and 4-point bend tests	Carbon fibre composite repaired steel riser	Full-scale
Rodriguez and Ochoa [328]	4-point flexural test, fatigue test	Carbon and glass fibres/epoxy	Small-scale
Lindsey and Masudi [328,329]	Cyclic test, tension in sea water cases from 25 °C to 75 °C	Graphite epoxy composite	Small-scale
Soden et al. [330]	Flexure test, tension test	Composite pipes and coupons	Small-scale

Another full-scale assessment was an RPSEA projected reported by Alexander et al. [105] on the performance of a composite-reinforced steel drilling riser for HPHT operating conditions using three prototype models with a bore diameter of 495.3 mm. It was subjected to cyclic testing under a service temperature range from 180 °F to 32 °F, a 20-year service life, top tension capacity of 13,333 KN, an internal pressure of 66,667 KN and operation in a water depth of 3048 m. Salama et al. [89] presented an investigation with the test certification for the first installation offshore on the composite drilling riser (CDR) joint, which includes bending fatigue, burst, impact testing and one pressure cycle at 31,712 kPa and two pressure cycles at 42,743 kPa. The Heidrun CDR joint seen in Figure 2, featured titanium connectors and a titanium liner, which was the first application of a composite offshore [88,89]. Titanium was chosen due of its low wear resistance. Secondly, the Heidrun TLP required a lighter marine riser joint so the CDR joint was made of titanium and 3 mm internal hydrogenated nitrile rubber liner seal. The composite drilling joint was visually inspected after the third drilling cycle, and no damage to the interior elastomer liner was found. As a result of this, DNV began developing specifications and guidelines for composite risers and composite fittings. Furthermore, given the lack of specifications and guidelines on composite risers and structural components, such as its end-fittings, extensive research on composite risers is required. As such, it is necessary to consider the pyramid principle for structural analysis and testing, as shown in Figure 20.

Figure 19. Composite riser pressure test samples (Courtesy of Lincoln Composites).

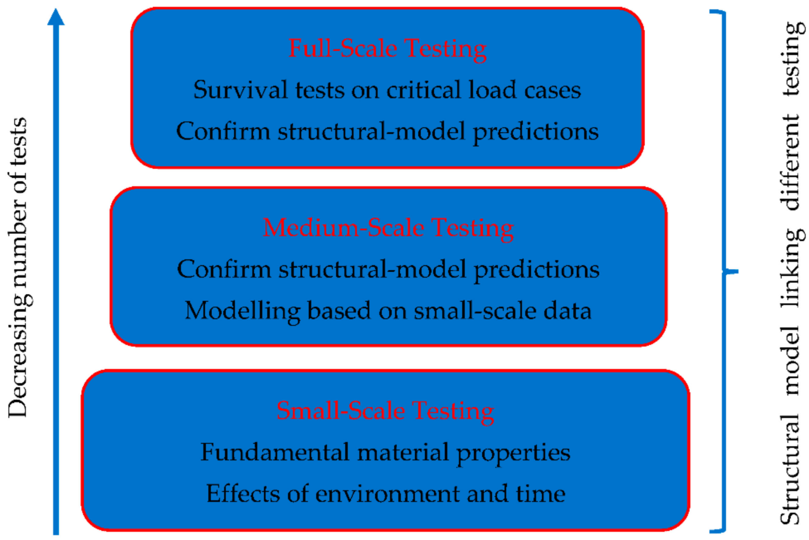

Figure 20. Pyramid principle for structural analysis and testing.

Based on load transfer mechanisms, composite structures are designed to transport loads via the fibre directions; hence, slight changes in the transverse directions have little impact on the load distribution in the structure, as depicted in Figure 13. This was demonstrated in the experimental model [134,257]. Layup sequence of composites are important aspect of the design. Ye et al. [257] carried out microscale and macroscale design of the composite CPR structures, using cylindrical coupons with fibres aligned at $+45°/-45°$ orientations. The study included characterisation of the composite materials and tested them with Imetrum test equipment and SEM and CT digitisers [257].

It is noteworthy to state that both thermal and mechanical analyses are critical for characterising polymeric systems, as demonstrated by Sobrinho et al. [224]. In that study, composite risers were developed from composite tubes that were 1.8 m in length, had an internal diameter of 0.1016 m and were 5.6 mm thick, with findings that the influence of matrix toughening on mechanical behaviour has a significant impact on composite fracture processes. The composite tubes were filament-wound, with the reinforcement fibres neatly tucked into the polymeric structures. They noticed that the tensile strength of the hoop layers increased to 709.05 MPa from 572.20 MPa, having a jump of around 20%, indicating that the addition of rubber to that polymeric matrix encouraged a simultaneous increment in elongation under both fracture and stress conditions. In another study on characterisation, Elhajjar et al. [322] created a profiled 3D model of the superficial resin pockets using the hyperspectral spectroscopy–infrared technique. The large ply approach was used to establish the random wrinkle distribution in the specimen, with the capacity to quantify resin thickness from around 125 to 2500 µm. His findings reveal varied failure modes when the specimen transitioned from a restricted fibre kink band configuration to a random wrinkle distribution. In a recent study by Chen et al. [186], experiments on scale-down prototypes with similar tensile-bending capacity to the tubular model were carried out to evaluate composite riser joints, and it indicated progress in tensile-bending capacity, similar to the findings by Toh et al. [187] and Meniconi et al. [78]. The implication is that the traplock end-fitting and the central tubular segment are both equally strong.

3.6. Numerical Analysis

Numerical analysis on composite risers is critical for ensuring the validity and accuracy of the chosen discretisation by examining its properties [140–144,148–151,331]. There have been a number of investigations on composite risers, including nonlinear failure analysis, mechanics and fatigue due to compression, tension, bending, torsions and their combined loading, internal fluid pressure and sea water hydrostatic pressure, as tabulated in Table 7. Bai et al. [248] investigated the internal pressure effect of a TCP pipe that was reinforced with a steel strip using ABAQUS and introduced a Mises yield failure criterion. Corona and Rodrigues [233] investigated the performance of long, thin-walled cross-ply composite tubes subjected to three phases of pure bending. Bifurcation buckling, material failure and prebuckling reactions were investigated utilising three different material models: AS3501 graphite–epoxy, Kevlar 49–epoxy and E-glass–epoxy. They discovered that the Brazier effect, which causes the cross-section of the tubes to ovalise, results in a nonlinear moment–curvature connection. Brazier [325] observed that the longitudinal stresses and compressions of thin cylindrical shells and other thin sections are orientated towards the toroid's median circumference. This causes flexural distortion by creating a proportional pressure per unit area at all places of the cross-section. Jamal and Karyadi [213] used Novozhilov's nonlinear thin-shell theory to compute the collapse of cylindrical shells under pure bending to investigate material failure. Tatting [228] used the semi-membrane constitutive theory for buckling studies to explore the brazier effect on composite cylinders of finite length under bending nonlinear analysis. He discovered that the tube length parameter has the greatest impact on the load–displacement response and local buckling failure. In another model, Guz et al. [218] solved the problem of the collapse pressure effect on thick-walled composite tubes using the elastic constitutive theory for the interlaminate layers for various loadings and stack-up designs. Elhajjar et al. [322] and Ye et al. [257] looked at composite failure reactions and faults in composite structures since these flaws can cause delamination, matrix debonding, fibre debonding, fibre kinking and matrix cracking. Li et al. [332] investigated the deformation of thin-walled tubes under bending with a small bending radius and a large diameter. To assist trials, Chen et al. [186] presented a numerical analysis for a prototype composite riser joint. The interface between the metallic liner and the composite laminate was modelled with ABAQUS using the traction–separation law to approximate splitting separation on a cohesive surface. Chouchaoui and Ochoa [225] investigated the behaviour of a laminated cylindrical tube with adequate boundary conditions at layer interfaces, i.e., without interfacial friction or sliding, though some presentations on the scaled models were further presented in another study [226]. Rodriguez and Ochoa [328] used both experimental and computational methods to investigate the effects of material systems, lay-up stacking and geometry on the failure behaviour of spoolable composite tubes under bending. They discovered that the tubes' nonlinear bending responses may be dominated by the drop in shear stiffness. External hydrostatic pressure was considered in the collapse investigation of a plastic composite–steel pipe (PSP) with an inner high-density polyethylene layer. A 2D ring model provided by Bai et al. [248,299] was also used to account for wall thickness variation, transverse shear deformation and prebuckling deformation in steel strip reinforced thermoplastic pipe. The numerical study of reinforced composite pipes for RTP made up of an exterior thermoplastic cover (PEEK), an inner thermoplastic liner (PEEK) and carbon-fibre-reinforced PEEK (AS4/PEEK) reinforcement layers was undertaken by Ashraf et al. [9]. They also evaluated the lay-ups ([75/50], [75/25], [50/75], [50/25], [50/25], [25/75], [25/50] and [25/50]). They discovered that pipes with two angle-ply reinforcement layers have a stiffer reaction than pipes with only one angle-ply reinforcement layer when the reinforcement layers are positioned at varied angles. In the finite element analysis (FEA) conducted by Rodriguez and Ochoa [328], shell elements were used in two-dimensional planes (2D-S8R) and an experimental four-point flexural experiment loaded to failure to match the structural features of filament-wound composite tubulars on huge spools to ABAQUS models. Since all of the composite tubes' failure modes were matrices in both tension and compression, and the shear stiffness showed a nonlinearity in flexure, he determined that damage was restricted to the bottom part and progressed slowly. Zhang et al. [66] looked at an analytical mechanical model of a composite riser pipe in both the global and local assessments and found the corresponding material characteristics. They concluded that the hoop layers generally bear internal pressures, while the helical layers mostly bear bend loadings, according to the simplified composite joint local analysis.

Table 7. Numerical analysis on composite risers, showing the test methods and mechanics studied.

Reference	Numerical Methods	Highlights
Bai et al. [248,299]	Numerical model, von Mises failure criteria	TCP Pipe, internal pressure ABAQUS
Andersen [8]	Minimum potential energy approach; failure criteria; progressive damage	Analysis of transverse cracks in composites
Rodriguez and Ochoa [328]	Numerical and experimental, spoolable tube bending; material failure mode; 2D shell element	Flexural response of spoolable composite tubular
Toh et al. [187]	Tensile strength assessment, mode shape from global response	Analysis of 2 composite riser end-fittings—taplock and Magma
Chen et al. [186]	Tensile strength, prototype design and analysis; composite riser joints	Numerical and test analysis of composite riser end-fitting; mechanical tests, tension and combined tension-bending loading tests of composite riser joints
Amaechi et al. [149–151]	Novel numerical approach in ANSYS ACP to model composite riser; netting theory; for 18 layers of composite riser	Buckling, burst, collapse, tension; under 6 load conditions, presented stress profiles for F.S of different layers in 3 stress directions, presented buckling modes
Jamal and Karyadi [213]	Collapse test; under pure bending; LR-739 composite cylindrical tube	Material failure using Novozhilov's nonlinear thin-shell theory
Corona et al. [233]	Nonlinear analysis using material failure criteria and constitutive modelling	Bending response of long and thin-walled cross-ply composite cylinders
Wang C. et al. [137–142]	Design of composite risers for minimum weight; Numerical method using ANSYS APDL to model composite riser.	Local design and global design of composite riser; design on min. weight, factor of safety results in 3 stress directions; Under combined loadings and global responses
Elhajjar R. et al. [322]	A hybrid numerical and imaging approach for characterizing defects in composite structures	Structural and elastic failure responses of composites; hybrid approach coupling with a progressive FEA

Table 7. *Cont.*

Reference	Numerical Methods	Highlights
Tatting, B. F. et al. [228]	The Brazier effect for finite-length composite cylinders under bending	Numerical nonlinear analysis using semi-membrane constitutive theory for the analyses.
Brazier L.G. [325]	Analysed the flexural behaviour of thin cylindrical shells and other thin sections	The flexural behaviour of thin cylindrical shells and nonlinear bending analysis

3.7. Fatigue Behaviour

Reliability of composite risers has been a discussion in recent studies due to uncertainty about the fatigue and other mechanical behaviours of the riser [156–158]. Fatigue is a type of failure that occurs in constructions subjected to dynamic and changing forces [333]. Risers are dynamic structures that respond to a wide range of loads and pressures. Dropped objects, anchor strikes, anchor dragging, trawling and boat collisions can all cause fatigue damage to risers during operation [23–25,334]. Fatigue has been a key design difficulty for ultra-deep-water risers due to irregular waves produced by varying amplitudes in the sea, as well as the influence of friction as the tubes slide against their conduits. Various research has been carried out to investigate the fatigue behaviour of composite risers using basic approaches that were originally developed for composite tubes and pipes made of other materials based on durability in water [335–341]. A summary of these fatigue studies are given in Table 8. Fatigue damage analysis using Miner's rule summing produces a permissible fatigue damage ratio of 0.1 for production and export risers and 0.3 for drilling risers, with S-N curves being those most typically utilised [23,24]. Connaire et al. [334] used the Newton–Raphson method and quasi-rotations to investigate the path-dependent nature of rotations in three dimensions in subsea risers, as well as the sensitive load cases of nonlinear loading regimes. In some other studies, composite riser repair systems were investigated [6,7]. In the study by Chan [6], the flexural strength of composite-repaired pipe risers was assessed with the laminate orientation of carbon–epoxy-fibre-reinforced polymer. Since the simulation and testing results differed, they realised that the bonding between the CFRP and the steel pipe surface needed to be examined.

Table 8. Fatigue tests on composite risers with the scale of the testing.

Reference	Highlights and Test Modes	Method Used	Specimen Type	Program/Test Scale
Thomas (2004)	Fatigue test	S-N approach	Composite riser	Full-scale
Huybrechts [302]	Fatigue test, fatigue life estimation	S-N approach	Composite tube	Full-scale
Salama et al. [89–91]	Fatigue test	S-N approach	Composite riser	Full-scale
Chouchaoui and Ochoa [225,226]	Fatigue test	S-N approach	Composite coupons	Small-scale
Sobrinho et al. [223]	Application-based test	S-N approach	Composite coupons	Small-scale
Mertiny et al. (2004)	Fatigue test	S-N approach	Composite coupons	Small-scale
Cederberg [109]	Fatigue test, fatigue life estimation	Strain-life model	Composite riser and steel-reinforced drilling riser	Large-scale
Kim [98]	Fatigue life estimation	Semi-log S-N approach, Power law S-N approach	Composite riser tube	Large-scale
Echtermeyer et al. (2002)	Fatigue life estimation	S-N approach	Composite tube	Small-scale

Table 8. *Cont.*

Reference	Highlights and Test Modes	Method Used	Specimen Type	Program/Test Scale
Liu K. et al. [291]	Fatigue life estimation	S-N approach	Composite tube	—
Yu K. et al. [148]	Fatigue life estimation	S-N approach	Composite tube	—
Sun S.X. et al. [163]	Fatigue life estimation	S-N approach	Composite tube	—

Two general fatigue techniques mentioned in the literature are cumulative fatigue damage (CFD) and fatigue crack propagation (FCP). Riser fatigue is a DNV-recommended practise. The design and evaluation of riser fatigue, as well as its global analysis and usage of S-N curves, are all covered by DNV-RP-204:2010. Crack initiation is when a small crack appears at a high-stress-concentration location; fracture propagation is when the crack increases progressively with each stress cycle; and final failure is when the progressing crack reaches a critical size and fails quickly [333]. Hybrid composites improve composite functionality by allowing the designer to add selectivity, including stiffer, more-expensive fibres where stresses are more critical and less-expensive fibres where stresses are less critical [3,102,117,255]. As water depths have increased and service conditions have become more demanding, manufacturers of nonbonded flexible pipes are attempting to build pipe cross-sections incorporating carbon fibre parts to solve these concerns [342–350]. Carbon fibre's most notable application has been in the substitution of heavy and expensive steel parts in nonbonded flexible riser pipes [5,22,119,215]. In an early design of a composite riser design with an ID of 220 mm, the analysis of lamina stresses compared to lamina strengths at each phase was progressive, as failure was discovered when the elastic constants of the lamina involved were modified [78]. Another study of nonlinear dynamic analysis and fatigue damage assessment using random loads on a deep-water test string found that fatigue damage varied with water depth, and the von Mises stress was higher in the string portions near the top of the test string and the flex joints [291]. Strength and the modulus are two key structural properties in load-bearing applications. By definition, the modulus of a material is a measure of its stiffness or resistance to elastic deformation, whereas the strength is the maximum force it can withstand before breaking.

3.8. Comparative Case Study

An earlier comparative study is the Heidrun composite drilling riser joint shown in Figures 2 and 19. One joint was tested for burst and two joints for bending fatigue as part of the qualification programme conducted by DNV. In addition, a number of joints were constructed to demonstrate the manufacturing process and to test impact resistance. All of the test joints had a diameter of 56 cm. Figure 21 depicts a model diagram of the MCI end fitting as well as one of the test specimens manufactured as an aspect of the qualification programme. The full-length (15 m) composite riser joint was installed on Heidrun TLP in July 2001, and pressure tested on well A-41. After that the joint was utilised to drill more than ten wells while being installed at varying positions located along the riser string. As shown in the results presented in Table 9, it can be observed that some findings were made under different tests including fatigue.

In a comparative assessment between composite risers and steel risers by 2H Offshore [199], there were benefits obtained from the application of composites on deep-water risers. The highlights of the fatigue investigation are given in Figure 22; comparing the steel riser and the composite riser shows that there was an improvement in the use of composite risers. Due to the highly rated fatigue performance of the composites and the elimination of welds along the structure, the riser experienced significant improvement in its fatigue performance. The steel stub positioned below the buoyancy tank suffered a 33.0% drop in fatigue life due to the reduced buoyancy. In addition, regarding the upper section, it was observed that the weld nearest to the upper-riser assembly (URA) interface was discovered to be the steel riser's fatigue hot point. On the other hand, the fatigue hot zone for the composite riser lies below the buoyancy tank steel stub, where the fatigue life was 200% higher than the steel riser minimum fatigue life. Details on the results of the comparative study are presented in Tables 10 and 11.

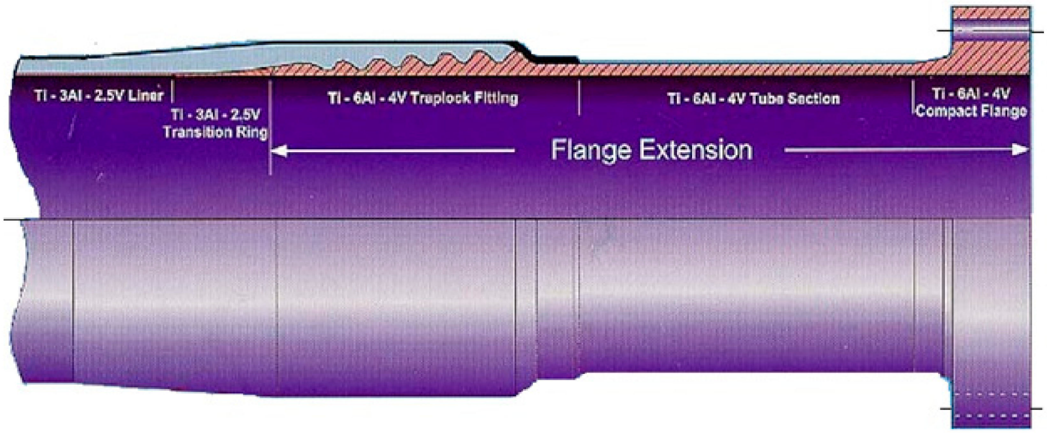

Figure 21. The Traplock end-fitting of the first composite riser joint showing the MCI sketch of the composite drilling riser by NCAS/KOP on the Heidrun Platform. [Permission was obtained from Elsevier Publishers, Source: [65,66,199]; Published: 12 July 2005; Copyright date: 2005].

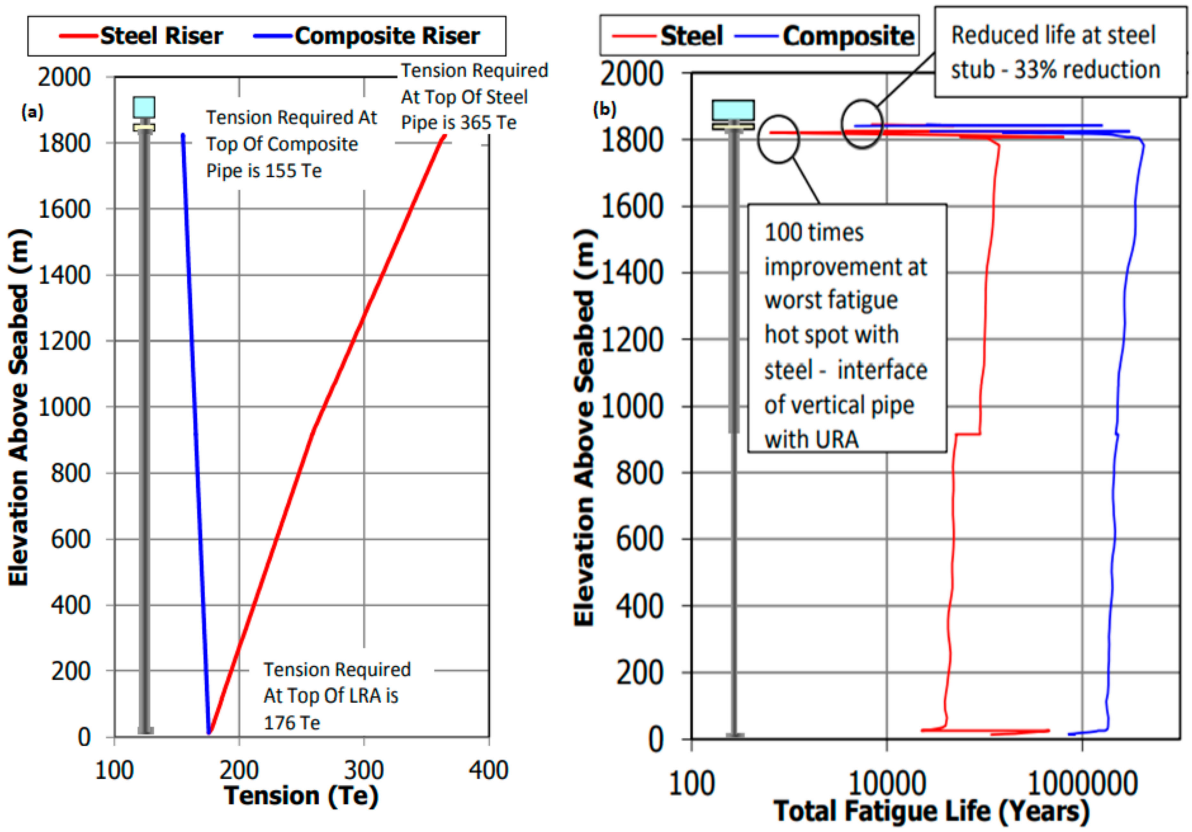

Figure 22. Comparative study on composite riser and steel riser, showing (**a**) tension and (**b**) fatigue life (Courtesy of 2H Offshore; Source: [199]).

Table 9. Results of composite riser joints with 22″ ID by ConocoPhillips/AkerKvaerner (Source: [65]).

Type of Test	Prediction Result	Measured Result	Failure Location
Burst pressure test with closed end loads	14,800 psi	15,850 psi	Body failure
Impact with 5000 kg m (36,170 ft-lb) dropped casing	No structural damage	No structural damage	No failure
Cyclic bending stress range of 850 kN m (627,000 lb-ft), cycles	140,000 psi	160,000 psi -180,000 psi	Circ weld in the Titanium (Ti) liner

Table 10. Comparison of the main design aspects of composite riser and steel riser. (Source: [199]).

Particulars	Steel	Composite	Observations
Max Hang-Off Load (te)	94	93	In an SLHR, the flexible jumper to the vessel acts as interface between the vessel and the vertical riser leg, thus keeping the two isolated. Therefore, negligible change in hang-off loads was seen
Max Hang-Off Bending Moment (kNm)	261	282	
Max Stress Utilisation	0.63	—	While stress is the driving criterion for steel, strain is the driving criterion for composites
Max Safety Factor	—	2.76	MBR is larger than minimum acceptable value
Max Tension Utilisation	—	0.14	Tension is low in comparison to the allowable tension
Max Buoyancy Tank Displacement (m)	247	211	Smaller drag area causes smaller buoyancy tank displacement
Max Buoyancy Tank Tension (Te)	451	258	43% less tension required
Max Bending Moment at Base of URA (kNm)	116	62	Approximately 50% lower bending moment from URA and LRA.
Max Bending Moment at Top of LRA (kNm)	581	270	

Table 11. Main results obtained for composite risers designed for 4000 m depth. (Source: [199]).

Particulars	Values	Observations
Pipe ID	8 in	This is the maximum recommended, and is driven by the collapse criteria
Pipe Max OD	11.9 in	The wall thickness can vary, and thus a smaller pipe OD can be used at shallower depths
Tension at Top	257 Te	Similar level to composite at 2000 m water depth. Note pipe size is different
MBR Safety Factor	2.84	Acceptable MBR
Max Tension Utilisation	0.17	Very low utilisation
Bending Moment At top of LRA	237.70	Similar to composite pipe at 2000 m
Bending Moment At base of URA	32.20	Similar to composite pipe at 2000 m
Maximum Flexible Joint Rotation	8.1 Degrees	Slight increase in comparison to 2000 m

LRA—lower-riser assembly, URA—upper-riser assembly, ID—inner diameter, OD—outer diameter, MBR-minimum bend radius.

4. Conclusions

This review has comprehensively looked at the design, mechanics and development of composite risers and their end-fittings for offshore marine applications. It has also shown current practices in the design of CPRs both from experimental and numerical perspectives. It is imperative that this review looked at different designs of CPRs to evaluate the new and challenging aspects. This review has shown that composites are a viable option for this application, as well as being technically feasible and showing certain improvements. Although there may not be a compelling case for using composites only on the basis of cost, newer configurations are advised. The end-fitting is a key factor in composite riser design, which has been successfully achieved. Overall, it is concluded that the cost of adopting a composite pipe in the existing SLHR system is comparable to that of steel. In addition, the mechanical performance was enhanced. According to several studies, the low use of composites in the offshore sector is due to the comparatively low technological maturity of polymeric composites. The real kicker is the dearth of appropriate test data and well-established design codes. Finally, unlike CPRs, continuous incremental advancements in steel and titanium alloys, as well as nonbonded riser pipes, have kept up with mammalian evolution. Due to their superior fatigue, high corrosion resistance, low specific weight, high stiffness along the reinforcing fibre orientations and high-strength features, these innovative composite materials could be beneficial for use in a variety of offshore structures. However, there is a pressing need for fully adaptive standards to be developed that are uniquely suited to risers. Currently, ABS, API, DNV and ISO standards have successfully published some related recommended specifications for composite risers [167–171,269–272,313–315]. They were developed in response to concerns about composite riser design and the use of composite materials, but they do not all agree, as they are based on the findings from technical committee (TC) meetings and prior composite research. However, a unifying standard for composite risers is expected in future.

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Abbreviations

2D	two-dimensional
3D	three-dimensional
6DoF	six degrees of freedom
ABS	American Bureau of Shipping
API	American Petroleum Institute
ATP	advanced technology program
BOEM	Bureau of Ocean Energy Management
BOP	blow-out preventer
CALM	catenary anchor leg mooring
CDR	composite drilling riser
CFD	computational fluid dynamics
CFRP	carbon-fibre-reinforced polymer
CPR	composite production riser
CT	computed tomography
D	drilling riser
D&P	drilling and production
DNV	Det Norske Veritas
FAT	factory acceptance test
FCP	fatigue crack propagation
FEA	finite element analysis
FEM	finite element model
FOS	floating offshore structure
FPSO	floating production storage and offloading
FPS	floating production storage
FRP	fibre-reinforced polymer
HNBR	hydrogenated nitrile butadiene rubber
HPHT	high pressure
ID	inner diameter
ISO	International Organization for Standardization
JIP	joint industry program
LRA	lower-riser assembly
MBR	minimum bend radius
MCI	metal–composite interface
MWL	mean water level
NASA	National Aeronautics and Space Administration
NIST	National Institute of Standards and Technology
OD	outer diameter
OTC	Offshore Technology Conference
P	production riser
PCSemi	paired-column semisubmersible
PA	polyamide
PE	polyethylene
PEEK	polyether ether ketone
PP	polypropylene
PSA	Petroleum Safety Authority
PSP	plastic composite–steel pipe
PVDF	polyvinylidene difluoride
RAO	response amplitude operator
RPSEA	Research Partnership to Secure Energy for America
SCR	steel catenary riser

SEM	scanning electron microscope
SLHR	single-leg hybrid riser
SON	Standards Organisation of Nigeria
SPAR	single-point anchor reservoir
SURF	subsea umbilicals, risers and flowlines
SURP	subsea umbilicals, risers and pipelines
TC	technical committee
TCP	thermoplastic composite pipes
TLP	tension leg platform
UK	United Kingdom
USA	United States of America
URA	upper-riser assembly
UTL	ultimate tensile load
VIV	vortex-induced vibration

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