Article

Guidelines on Composite Flexible Risers: Monitoring Techniques and Design Approaches

Chiemela Victor Amaechi 1,2,*, Ahmed Reda 3, Idris Ahmed Ja’e 4, Chunguang Wang 5 and Chen An 6

1 Department of Engineering, Lancaster University, Bailrigg, Lancaster LA1 4YR, UK
2 Standards Organisation of Nigeria (SON), 52 Lome Crescent, Wuse Zone 7, Abuja 900287, Nigeria
3 School of Civil and Mechanical Engineering, Curtin University, Bentley, WA 6102, Australia; ahmed.reda@curtin.edu.au
4 Department of Civil Engineering, Universiti Teknologi PETRONAS, Seri Iskandar 32610, Malaysia; idris_18001528@utp.edu.my
5 School of Civil and Architectural Engineering, Shandong University of Technology, Zibo 255000, China; cgwang@sdu.edu.cn
6 College of Safety and Ocean Engineering, China University of Petroleum—Beijing, Beijing 102249, China; anchen@cup.edu.cn
* Correspondence: camaechi@lancaster.ac.uk

Received: 5 June 2022
Accepted: 4 July 2022
Published: 7 July 2022

Abstract: The increasing energy demand has led to more explorations in the oil and gas industry. To achieve this, marine risers and pipelines are used to convey fluid and other resources to meet the increasing demand. In recent years, hybrid flexible composite risers have become more adaptable. Flexible risers have already proven to be a popular riser solution for various floating production systems in shallow to deepwater in many parts of the world due to their good dynamic behaviour and dependability. The hybrid flexible composite riser is made up of numerous layers of plastics, flexible pipes, composites, and steel. Some innovative monitoring methods, such as Fiber Optics Bragg Gratings (FBG), are based on a clamped composite structure with embedded optical fibre. This study presents characteristics of the monitoring techniques of composite flexible riser technology. The advantages of the monitoring techniques include aiding composite riser measurements, recording data from riser deformation, improving integrity assurance, and dependability of design from stable readings. It also proposes some design approaches as guidelines that are advised, with some policy implications.

Keywords: monitoring; offshore platform; flexible riser; composite riser; riser; guidelines

1. Introduction

The increasing energy demand has led to more explorations in the oil and gas industry. To achieve this, marine risers and pipelines are used to convey fluid and other resources to meet the increasing demand. In addition, offshore platforms are designed to have structural components and conduits for extracting oil and gas products to provide energy [1–3]. However, the structural strength of aeronautical structures, subsea pipelines, cables, and marine risers is subject to certain limits, which also affect their service life and useability [4–7]. Conversely, an engineering challenge faced by pipe designers includes sustainable design methods, safe operating procedures, and better monitoring techniques [8–11]. The safety and protection of SURF (subsea cables, umbilicals, risers, and flowlines) systems have increased demand in the industry [12–17]. Aside from protection, material choice is also important for long service and for preventing any structural failure. Hence, the reliability of the engineering material is important and requires some monitoring. However, the strengths of engineering materials, such as steel and composites, differ.

Steel has long been utilised in the oil and gas sector throughout the hydrocarbon value chain, from wells and rig equipment to onshore pipelines, marine risers, subsea cables,
storage tanks, and refineries [18–22]. Composites, on the other hand, are gaining popularity due to the multiple advantages they provide over traditional building materials, such as steel and aluminium [23–28]. The use of composites decreases the total weight of the structure, improves corrosion resistance, lowers overall operational costs, and allows for more design freedom [29–34]. Risers, drill pipes, tubes, pressure vessels, tanks, and other fluid conveyances are also made of materials, such as composites. Each of these components utilises some monitoring measurements during design, testing, and qualification. Figure 1 shows an experimental setup showing some sensors for monitoring strains on a composite pipe sample under pressure loading.

The structural integrity of composite materials, subsea cables/pipelines, and marine risers are very important [35–40]. However, these systems are applications that require adequate monitoring when deployed on offshore facilities. Zumpano et al. [40] investigated the integrity of pipelines using sensors to take readings, which indicated that the base material must also be resistant to sulphide stress corrosion cracking. Aside from corrosion, monitoring helps in several other areas to ensure the long-term integrity of the cladding or overlay as a protective layer for any pipeline under anticipated service circumstances. However, an industry challenge is the early detection of failure on composite structures, such as delamination and ply failure, hence the need for more monitoring techniques, such as the use of fibre-optics sensing [41–46]. Different monitoring sensors and monitoring techniques are used on composite structures and optical fibre materials [47–50]. One such technique is the Rayleigh backscatter via its Optical Backscatter Reflectometer (OBR) and the use of a distributed fibre optic network to identify accidental impact damage early [51–56]. This method delivers high spatial resolution strain and temperature measurements from several sensors placed all along the optical cable.

Since armour layers are critical to the structural integrity of flexible risers, operators, and service providers around the world are still looking for reliable inspection or mon-
itoring techniques that can detect the presence of cracks or other defects in the metallic wires that make up the pipe’s internal and external armour layers. OBR is a monitoring technique that has also been successfully used on both flexible risers and composite materials [35,57,58]. However, other structural health monitoring (SHM) systems have been developed, as well as advances made from SHM technology, which demonstrate the benefits [59–65]. As a result, distributed sensing is one of the best methods for identifying local cracks that could lead to ply-failure initiation in real applications. Another object of current inventions on monitoring is to provide a structural integrity monitoring system for determining strain concentrations and local anomalies by measuring average strains in the metal-to-composite end connection of composite tubulars, including risers, using the Optical Time Domain Reflectometry (OTDR) optical fibre strain measurement method in the metal-to-composite end connection of composite tubulars, including risers. Wrapping the optical fibres around the outside of the composite structure and attaching them to the composite material with a bonding agent such as epoxy, as well as protecting the optical fibre with the bonding agent and an additional outside protective layer of polymer or rubber-like material, is the preferred method.

The study proposes some guidelines for composite risers, with some design approaches and monitoring techniques. Section 1 introduces the subject to be discussed, while Section 2 presents the materials and monitoring techniques. Section 3 presents the methodology and design approaches. Section 4 presents the application and case studies of composite risers. The concluding remarks are presented in Section 5.

2. Materials and Monitoring Techniques

This section presents a discussion of the materials and monitoring techniques.

2.1. Composites for Marine Risers

Marine risers are a form of pipeline built to vertically transport fluid from the seabed to production and drilling facilities above the water’s surface, including from the facility to the seafloor, and vice versa. These risers serve as a link between subsea field developments and production and drilling facilities, whether as production or import/export vehicles. Marine risers transmit generated hydrocarbons as well as production materials, such as injection fluids, control fluids, and gas lifts, similar to pipelines or flowlines. By classification, marine risers can be rigid or flexible. Due to their application, marine risers are usually insulated to resist seabed temperatures. Different researchers have presented different studies on monitoring of marine risers, such as fatigue monitoring using shape-sensing devices [53,66–69], fibre-optic monitoring [54,70–73], intelligent systems [74–76], optical sensing [51,77–81], Riser Integrity Management (RIM) [82,83], flexible pipe integrity assurance [36,69,84], pipeline condition monitoring [85–87], vibration monitoring for armour failure [63,67,68,86], pipeline surveillance monitoring [88], and leak detection systems [76,86,89–91].

Flexible risers have good dynamic behaviour and reliability, which makes them one of the favoured riser solutions. Riser systems are utilised on different floating production systems in shallow to deepwater in several parts of the world. There are also newer deployments of composites on flexible risers, called hybrid composite flexible risers [24,92–95]. The flexible pipe is made up of numerous layers of plastic and steel. The weight of the riser is supported by a huge number of steel wires (known as tensile armours) that are critical to the pipe’s integrity. As a result, it is critical to be able to ensure the integrity of those armour wires and to detect any potential failure early enough to intervene [58,96–98]. With the growing impact of structural monitoring, offshore structures can be monitored with better integrity management and improved reporting on the performance [99]. One method is to conduct sufficient fatigue studies on composite risers [98–102]. For large-scale assessments, Corrignan et al. [66] recommended that risers be inspected and then have a plan to re-terminate or partially replace it, if necessary. To address this operational and safety concern, novel monitoring devices can be used to identify tensile armour wire failure or conditions that could lead to failure. Some monitoring methods invented include
Technip/Schlumberger’s device which is based on a clamped composite structure with an embedded optical fibre that employs technologies such as Fibre Optics Bragg Gratings (FBG) [66]. It was reported further that the devised gadget can monitor permanent deformation (torsion and elongation) caused by an imbalanced equilibrium of the tensile armour layers, which can lead to armour collapse. Integrity assurance becomes more reliable as a result of these cross-referenced data.

Any production optimisation system must be able to accept high-quality data on demand to function properly. The reservoir monitoring sector has been tackling the issue of reliability over the past decade, including the use of a step-change technology called Passive Optical Sensing Systems [79]. Optical sensing devices were initially expensive, difficult to install, and could serve only a limited number of applications. In terms of performance, cost, and ease of installation, they are now on level with electronic gauges. Bragg-grating-based Pressure and Temperature sensors, permanent Distributed Temperature Sensing (DTS), Single-phase and Multiphase Flowmeters, and Seismic sensors are among the state-of-the-art optical sensing technologies [78,103,104]. Since the first in-well optical pressure gauge was installed over 20 years ago, the industry has established a solid track record, with several P&T gauge installations and DTS installations—and acceptance is growing. Drakeley et al. [79] presented the workings on each of the above-mentioned sensing systems, as well as the data and information provided, as well as applicable case histories. These range from modest single-gauge installations to elaborate Smart or Intelligent Wells with integrated pressure monitoring, flow metering, and remotely activated zonal flow control.

Intelligent completions and subsea installations will become considerably more sophisticated in the future. High-precision distributed array temperature sensing, optical distributed pressure sensing, sand detection, and distributed strain (for example, for riser monitoring) are only a few of the innovative sensing systems discussed in this study. Operators want in-well monitoring systems that provide high-performance measurements throughout the life of the well, as well as reliability without the need for routine maintenance or intervention, to manage and optimise well output. Optical sensing’s first applications in the 1980s were mostly in the military and aerospace industries [105]. Early optical sensing systems were driven by requirements that were not readily available in comparable electrical systems. The following were among the requirements:

- Small physical dimensions allow for easy integration in tight spaces and incorporation into composite structural systems.
- Various sensing points and measurement kinds on a single fibre, obviating the need for multiple electrical sensors, instruments, and connections. In aeronautical systems, this reduced system complexity and weight are crucial.
- Silica with high-temperature fibre coatings, allowing for the construction of sensing devices at temperatures above 1000 °C.
- High reliability is achieved by using basic sensing elements at the measurement point and keeping the sensor’s instrument in a serviceable or repairable position.
- Interference immunity from nearby radio or electrical transmission sources.
- There is no risk of fire due to the lack of a spark hazard.
- Optical communication methods also dramatically enhance signal quality, data density, and transmission distance.

These specifications are also appropriate for oil and gas in-well monitoring applications. Historically, the first in-well optical pressure and temperature gauge was installed in 1993 in a producing land well in the Netherlands, as the initial system worked flawlessly for more than five years [79]. So began the industry’s march towards a broader embrace of technology. A greater range of commercial optical sensing devices and services has been introduced to the oil and gas sector as a result of increased investment by service firms and operators in the development of sensor systems.

Recent utilisation of monitoring systems, as well as composites, has yielded results for marine risers in the industry. These have also led to the development of newer composite riser specifications [106–109]. Because composites are in high demand as a subsea
plumbing substitute for activities in deeper waters, there is increasing interest as their usage expands into thermoplastic composite pipes (TCP) for deep-sea oil and gas applications. Airborne Oil and Gas, a TCP manufacturer, was the first to construct and deploy an offshore TCP downline in 2009 [23]. The adoption of TCP was aided by the fact that it is less expensive and easier to transport, prepare, and install than steel. Today, it has been applied to composite flowlines and composite riser technologies. Currently, some oil operators have used composite materials over substantial areas of their oil and natural gas flowline networks. Additionally, Airborne Oil and Gas’ carbon fibre reinforced PVDF (polyvinylidene difluoride) has proven to save 30% more on as-installed cost than steel. In addition, Technip FMC’s Magma Global formed a joint venture to develop a new carbon fibre composite hybrid flexible pipe (HFP) for offshore applications, while Solvay and Baker Hughes have formed a joint venture to employ TCP in offshore flexible pipes and risers. Hence, there is increased application of advanced composite flowlines, composite risers, and other composite tubes.

This guideline proposes the consideration of designing the marine riser as a basis for making a choice riser with monitoring. Hence, the steel riser can be chosen as a benchmark from different marine risers for the design of composite risers. The steel riser can be modelled as a reference model used as a benchmark in composite riser research. Generally, the range of marine risers includes marine hoses, hybrid flexible risers, attached risers, pull-tube risers, steel catenary risers (SCRs), top-tensioned risers (TTRs), and riser towers. However, marine risers are broadly classified as drilling risers or production risers, although different riser types are considered for benchmarking purposes, as illustrated in Figure 2.

Figure 2. Different types of marine riser systems are considered for benchmarking composite risers.
2.2. Why Is Monitoring Important?

Due to various failure issues in subsea pipelines, monitoring has been an increasing challenge that needs to be tackled, such as corrosion and the need for composite pipe repairs [110–113]. Earlier studies have been conducted on acoustic measurements and monitoring [114–118]. Some of these studies include inspection and monitoring of flexible line systems like flexible pipes [119,120]. Current techniques use a diverse range of monitoring devices and techniques on marine risers and pipelines [11,121,122]. These techniques aid in the proper monitoring of composite tubulars to ensure the safety and structural integrity of the structure and to avoid accidents on the offshore field [69,83,123,124]. Hence, composite risers must be monitored regularly using different monitoring devices, monitoring techniques, and sensors. Sometimes, these composite risers, flexible risers, composite pipes, and subsea cables can have some failures that can be detected early and fixed. The easiest method that has been identified to cut costs is to conduct on-the-site repairs and at-the-spot repairs on the structure. Transporting the composite riser pipe is usually cost intensive, manpower intensive, and machinery intensive. Hence, newer monitoring techniques and devices must be embedded on the composite riser during service. Over time, there may be some failure on the composite riser or faults detected, which may require maintenance called early repair schemes. To ensure that the repair delivers the same strength and functionality as if no damage exists, careful monitoring is required. The long-term effectiveness of bonded repairs is unknown, and one of the goals of bonded repairs is to prevent critical problems. Monitoring can detect defects, such as debonding and delamination, which are both problems that affect the repair’s efficiency, hence the need to design with industry specifications [125–130]. Sensors are also used for marine risers for in-service feedback and to ensure that the structural health of the equipment is intact. Figure 3 shows a fatigue testing rig for composite marine riser with cables, sensors, and other monitoring devices.

There is a particular challenge in assessing the original damage when applying the repair; thus, the need to fix the damage arises. Since the damage is no longer visible, a new method of inspecting and monitoring it is required [10,50,131]. To maintain credible measurements, a proper monitoring technique must be used. According to Zumpano et al. [40], the rupture of the thickness of the Corrosion Resistant Alloy (CRA) layer becomes a failure mode due to the low resistance of carbon steel to corrosion fatigue in the presence of contaminants in the fluid content. When subjected to critical cyclic loads over the service life, an Engineering Critical Assessment (ECA) must be undertaken to determine whether circumferential planar faults in weld overlay zones would not spread through the CRA layer, exposing the underlying material. To estimate the maximum weld overlay pass height to be limited by machining, such an analysis would include fatigue crack growth simulation and the surface interaction of entire circumferential embedded flaws. A full circumferential defect should be able to endure the operational fatigue life due to the limited height of the machined layers. However, this is a time-consuming manufacturing method that raises further problems about out-of-straightness and out-of-roundness for long extensions. The ECA data might also be utilised to estimate the defect acceptability criteria and the needed probability of detection for volumetric non-destructive testing. In terms of project timing and production costs, recent innovations in ultrasonic inspection have been effectively adopted and represent better solutions. In terms of image quality indicators (IQI), radiographic testing can also be employed if it fulfils the needed sensitivity. Validation tests must be conducted in any case to demonstrate sufficient reliability in detecting the minimum flaw height needed. However, different monitoring systems are utilised in energy systems, such as on offshore platforms, as seen in Figure 4.
Composite risers must be monitored regularly using different monitoring devices, monitoring techniques, and sensors. Sometimes, these composite risers, flexible risers, composite pipes, and subsea cables can have some failures that can be detected early and fixed. The easiest method that has been identified to cut costs is to conduct on-the-site repairs and at-the-spot repairs on the structure. Transporting the composite riser pipe is usually cost intensive, manpower intensive, and machinery intensive. Hence, newer monitoring techniques and devices must be embedded on the composite riser during service. Over time, there may be some failure on the composite riser or faults detected, which may require maintenance called early repair schemes. To ensure that the repair delivers the same strength and functionality as if no damage exists, careful monitoring is required. The long-term effectiveness of bonded repairs is unknown, and one of the goals of bonded repairs is to prevent critical problems. Monitoring can detect defects, such as debonding and delamination, which are both problems that affect the repair’s efficiency, hence the need to design with industry specifications [125–130]. Sensors are also used for marine risers for in-service feedback and to ensure that the structural health of the equipment is intact.

Figure 3. A fatigue testing rig for composite marine riser showing sensors, cables, and other monitoring devices used (Reprinted/adapted with permission from Ref. [109]. Copyright year: 2014, copyright owner’s name: Prof. Andreas Echtermeyer, NTNU).
There is a particular challenge in assessing the original damage when applying the repair; thus, the need to fix the damage arises. Since the damage is no longer visible, a new method of inspecting and monitoring it is required [10,50,131]. To maintain credible measurements, a proper monitoring technique must be used. According to Zumpano et al. [40], the rupture of the thickness of the Corrosion Resistant Alloy (CRA) layer becomes a failure mode due to the low resistance of carbon steel to corrosion fatigue in the presence of contaminants in the fluid content. When subjected to critical cyclic loads over the service life, an Engineering Critical Assessment (ECA) must be undertaken to determine whether circumferential planar faults in weld overlay zones would not spread through the CRA layer, exposing the underlying material. To estimate the maximum weld overlay pass height to be limited by machining, such an analysis would include fatigue crack growth simulation and the surface interaction of entire circumferential embedded flaws. A full circumferential defect should be able to endure the operational fatigue life due to the limited height of the machined layers. However, this is a time-consuming manufacturing method that raises further problems about out-of-straightness and out-of-roundness for long extensions. The ECA data might also be utilised to estimate the defect acceptability criteria and the needed probability of detection for volumetric non-destructive testing. In terms of project timing and production costs, recent innovations in ultrasonic inspection have been effectively adopted and represent better solutions. In terms of image quality indicators (IQI), radiographic testing can also be employed if it fulfils the needed sensitivity. Validation tests must be conducted in any case to demonstrate sufficient reliability in detecting the minimum flaw height needed. However, different monitoring systems are utilised in energy systems, such as on offshore platforms, as seen in Figure 4.

Figure 4. Different monitoring systems utilised in an offshore production investigation, showing submarine buoy monitoring systems, ocean submersible monitoring systems, remotely operated vehicle (ROV), ice mass-balance buoy (IMB), Conductivity-temperature-depth (CTD) instrument, air–sea exchange flux monitoring systems, Ocean Monitoring System (OMS), etc. (Reprinted/adapted with permission from Ref. [131]. Copyright year: 2018, copyright owner’s name: Keia Publishers & China Geology Journal).

2.3. Monitoring System Requirements

There are numerous conditions for properly implementing the monitoring strategy in the provided application. It must first investigate a parameter capable of detecting appropriate failure scenarios. When it comes to detecting mechanical failure, such as the failure modes listed above, strain is one of the most important characteristics to consider because changes in strain will be present if any of them occur. Furthermore, a composite material’s strain response will not be uniform [128]. As a result, the monitoring system should have a sufficient spatial range to connect the readings to the entire repair rather than just one place. One application of composite riser technology is repairing the riser. The sensor used in the repair must be non-destructive and not cause system harm, such as weak points, crack initiators, or sharp corners. The repair and monitoring equipment will be used in a high-risk setting that is prone to electrical sparks. Aspects that could cause a fire must be avoided. According to Lamvik [10], it is vital to remember that the interface between the pipeline and the repair is the most important aspect to keep an eye on. This is the most likely location for debonding, and flaws at this interface are more serious than those at the plies’ interface because it is the sole load path [128]. As a result, this interface should be used to implement the sensing device.

Different researchers have applied diverse monitoring strategies to composite pipes [10,11,131,132]. Each chosen monitoring is conducted using the above-mentioned parameters while selecting an appropriate monitoring technique. The options for im-
plementation can be classified into two categories: embedded and surface mounted. In research by Lamvik [10], it was obvious that the optical backscatter reflectometer (OBR) was the best monitoring method to use. The OBR uses optical fibres as sensors, which may be placed in various orientations around the riser and provide a greater measuring range than the alternatives. The optical fibres can be inserted into the repair to monitor the desired position without affecting the repair significantly. The measurements were not affected by the surroundings. Pipa et al. [132] reported the use of the MAPS-FR probe, depicted in Figure 5, which is the basic component of the MAPS-FR apparatus also used for strain measurements on pipes. Each probe has an excitation coil that generates the electromagnetic field that travels through the wires of the riser, as well as three sensor coils that detect the response of a wire or set of wires to the excitation field. The value received by the sensing coils is determined by the force placed on the wires.

![Figure 5. The MAPS-FR probe on a pipe sample (Reprinted/adapted with permission from Ref. [132]. Copyright year: 2010, copyright owner’s name: Springer Nature).](image)

### 2.4. Leak Detection System

One of the requirements of any detection system is to obtain preliminary data from the risk analysis to evaluate the safety, social, and environmental consequences of a containment breach [89,90]. It will be able to examine a strategy for early detection of a loss of containment, as well as a specific method or technology, based on this requirement. A leak detection system allows for risk management in this regard: the earlier the leak is noticed, the faster the pipeline operator can deploy emergency plan countermeasures.

The methods of early detection can be divided into two categories:

- “Direct” approaches based on fluid detection or “direct” observation following containment loss;
- “Indirect” or “deductive” methods deduce the probability of loss of containment based on the evolution of measured pipeline operating data.

One of the most promising “direct” leak detection solutions is fibre optics. The mechanism of light backscattering within the fibre can be exploited to convert the fibre core used for telecommunication into a sensor. With real-time analysis of the light backscattered when passing a light pulse through the fibre, distributed temperature or acoustic profiles can be acquired [89,90]. However, the demand for performance enhancement is continuously increasing as pipeline leak detection systems become more widely deployed in the oil,
According to Zhang et al. [133], the following leak-detection technologies are applicable to various pipelines, as follows:

i. Transient model in real time;
ii. Statistical analysis;
iii. Negative pressure waves; and
iv. Fibre optics.

These technologies show different performance figures, which show the least leak detectable, the time of detection, the accuracy of leak location, and the rate of false alarms. The future of leak detection is promising, with possible combinations of different technologies examined to provide the best available solution and optimum environmental protection. Other technologies that apply monitoring systems are real-time ship tracking in the maritime industry as seen in Figures A1 and A2, and monitoring of climatic weather as well as ocean weather conditions as seen in Figures A3 and A4.

2.5. Reflectometer for Optical Backscatter

Sensors that interpret and analyse light reflections in optical fibres are referred to as fibre optic sensors (FOS). Distributed fibre optic sensors (DFOS) generate temperature or strain fields based on the scattering process in the optical fibre, which is decoded by software [134,135]. The optical fibre has a tiny diameter of 155–195 μm, a high spatial resolution, and is sensitive enough to detect minute changes while maintaining a wide measurement range. The measuring range can be very extensive, ranging from one to several thousand metres, although the length will reduce the measurement’s spatial resolution. Spatial resolution refers to the precision with which data are captured, which can be as low as 1 mm [10,136].

The optical backscatter reflectometer (OBR) is a device that uses optical fibres to detect changes in strain. The programme allows for continuous measurements along the optical fibre’s whole length. The optical fibre, referred to as the main fibres, is carefully positioned across the areas to be examined and connected to the OBR via shielded optical fibres, referred to as secondary fibres. When composite production equipment is removed, the optical fibre is commonly embedded in composites or polymers, but it can easily break. Optical fibres are typically installed in the composite fibre direction [137,138]. The OBR generates a probe signal by emitting a laser beam from the light source. Rayleigh backscattering is caused by natural flaws or a fluctuating reflective index along the length of the optical cable. The detected signal is backscattering, which provides continuous sensing locations along with the optical fibre based on information from the reflected pattern and backscatter time. When the optical fibre deforms, the reflection pattern changes. The signal can be turned into a function of length by comparing it to a reference signal. The strain response will cover the entire length of the optical fibre in a single test and provide information about the structure’s overall behaviour. Two-dimensional strain fields can be created by arranging the optical fibres in a grid. In the programme, parameters such as gauge length and sensor spacing are defined, which specify the virtual sensors along the length of the optical fibre. Strain is calculated by averaging the backscattered signal’s displacement over the gauge length for each virtual sensor [138]. The measurement points will overlap if the gauge length is greater than the sensor spacing. The sensing length divided by the sensor spacing gives the number of measurement points. The best mix of these factors is different for each measurement, as data with a short gauge length will contain more details, while measurements with a long gauge length will reduce scatter in the measurements [10]. OBR is a relatively new technology for strain measurements that has been shown to be a promising measurement technique [10,136–140]. Since optical fibres have been applied practically, although they are typically time-consuming and difficult, they have contributed to research findings [60,141–143].

The OBR was utilised by Grave et al. [137] to measure the strain field emerging in a composite patch glued to a metal I-beam during a four-point bending test. There was a 20 mm machined crack in the centre of the top flange of the I-beam, which was terminated.
by a 6 mm hole. The composite patch was made of carbon fibre composite with a galvanic protective layer of chopped strand mat below. The optical fibre was installed in two places: one was embedded in the composite laminate and would measure the strain arising from the adhesive contact, while the other was positioned on the composite patch’s surface. For comparison, four electrical strain gauges were mounted on the patch surface. The strain obtained from the physical test at high loads differed from that derived from the linear finite element analysis (FEA) in the Abaqus model. The reason for this was damage development in the composite, which was not accounted for in the FEA but demonstrates the OBR’s ability to detect damage early. High strain gradients resulted in noise in the measurements, which may have been reduced with postprocessing. Finally, OBR was used to successfully assess the repair.

Optical fibres can be inserted into composite materials using OBR to assess structural health in composite pressure pipes to investigate impact and burst tests [139]. The optical fibre design allowed for high-resolution strain measurements throughout the whole surface of the pressure vessels. Optical fibres are normally inserted parallel to the composite layup, but this is not always the case with filament wound constructions. The optical fibres were placed between the hoop layers, although the pitch angles of the optical fibres and the composite layup varied. The optical fibres were spaced 20–30 mm apart, resulting in a pitch angle of 2.6°–3.9° for the optical fibres and 0.65° for the composite fibres. In addition to vacancies, this offset creates resin-rich patches around the optical fibres, and if the composite material fractures owing to high levels of pressure loads, the matrix cracks can cause significant local strains around the optical fibre, disrupting the signal. The variation in pitch angle, on the other hand, is tiny and produces only minor disruptions to the laminate, with no significant effect on the composite’s qualities. Optical fibres were also used in a grid in the centre of the pressure vessel to detect strain caused by impact loads.

When disassembling from the filament winding machine, several fibres failed at the point where the fibre egressed from the laminate; only 50% of the optical fibres were intact after manufacture. According to Lamvik [10], this problem was overcome by placing a patch of glass fibre composite over the area where the optical fibres were vulnerable, and almost all fibres remained undamaged. In that study, strain measurements were carried out with the help of LUNA OBR 4600 [134,135]. The resolution can be changed by adjusting the sensor spacing and gauge length parameters. The gauge length is essentially the length of a virtual strain gauge, and the sensor spacing is the distance between these strain gauges. Unlike regular strain gauges, these virtual strain gauges can overlap. Saeter et al. [139] used three different sets of parameters in their experiments: gauge lengths of 5, 10, and 30 mm, and sensor spacings of 1, 5, and 10 mm, respectively. With a gauge length of 5 mm and a sensor spacing of 1 mm, a very fine spatial resolution is achieved; however, local variations in the data may occur. These oscillations can be averaged and thus avoided with a coarser resolution if the strain field is close to a homogeneously high spatial resolution is not required.

An important aspect of this monitoring study is acoustic measurements. It is not uncommon for noise to be present in measurements. As the load levels increased, the strain measurements became noisy, as noted by Saeter et al. [139]. Noise can be caused by faulty splices, improper connections, or excessive curvature in the secondary or primary coated optical fibre. Damages to the optical fibre itself, such as hits or probable voids, can result in a signal with disruptions.

As previously stated, when the orientation of optical fibre and composite fibre differs, voids, and resin-rich areas are widespread; therefore, a bigger pitch offset results in higher noise levels. Noise can be introduced by post-processing, and some strain calculation settings can increase noise. The trials conducted by Saeter et al. [139] served as the foundation for a subsequent report by Lasn et al. [140], one of the main goals of which was to localise the damage detected by the OBR. When studying impact damage, the simplest detection method depends solely on the backscattered signal from optical fibres. In the measurements, the end of the optical fibre appears as a high peak. If the optical fibre breaks
owing to a heavy load, the end of the fibre, and hence the peak in the measurements, will shift. This method is easy and effective; however, it is only effective if the fibre breaks. This will also limit the amount of data that can be collected in future measurements.

When a network of optical fibres was subjected to an impact load, stresses were computed by Lasn et al. [140]. To locate the damage, a strain map was created in post-processing, with a dot representing the strain value and a hoop and axial position indicating its location. A larger dot denoted a higher strain value. This not only helped to locate the damage, but it also helped to visualise the contour of the damage. The helical orientation of the composite fibres, which were coiled at a 15° angle to the axial direction, coincided with the orientation of the damage [10]. The strain was measured using a running reference approach rather than matching each measurement to an initial reference in the studies conducted by Heinze et al. [141] and Saeter et al. [139]. The running reference method calculates strain by comparing each measurement to the preceding one, and then combining the strain differences to get an absolute amount of strain. When the optical fibre is subjected to specific physical conditions, such as microbending or pinching, noise enters the measurements, and the strain values produced are not always useful. In situations when the standard method fails, such as the previously indicated conditions for the optical fibre or very high load levels, the running reference method obtains meaningful strain values with reduced noise [139]. It was further reported that noise will be present at high levels of pressure loads (near failure) and around damaged areas, although it can be misinterpreted as a symptom of damage, such as matrix cracks.

When composite materials are subjected to impact loads, they are prone to delamination, especially near free edges. The OBR was utilised by different researchers to detect and localise delamination [59,60]. In the study by Diaz-Maroto et al. [60], the colour strain map and the ultrasonic inspection of the sample investigated were able to visualise the first ply failure and delamination in the sample, as seen in Figures 6 and 7.

Figure 6. Delamination region to visualise failure on the ply when the Ultrasonic C-Scan inspection plot is zoomed (Reprinted/adapted with permission from Ref. [60]. Copyright year: 2016, copyright owner’s name: UPM, NDT & Patricia F. Díaz-Maroto).

Figure 7. The result after the impact of 6.8 J shows the strain map (Reprinted/adapted with permission from Ref. [60]. Copyright year: 2016, copyright owner’s name: UPM, NDT & Patricia F. Diaz-Maroto).
Optical fibres were inserted and attached to the surface in a dense network with 5 mm spacing between each fibre. The optical fibre linked to the surface will experience residual strains because of delamination, indicating the location and level of damage. Delamination was detected via experimental tests on composite laminate plates with a $[0_n/90_n]$ layup, with the number of layers $n$ varying between 2 and 4 for different specimens. A drop weight testing machine was used to provide impact stress to the specimens. Delamination was discovered on both the edge and near edge of the board. Delamination was identified and confirmed by visual inspection in the first example. The damage in the latter example was internal and could not be seen with the naked eye but was confirmed by ultrasonic C-scan inspection. The measurements revealed a delaminated zone with a residual strain field change of 200. Finally, OBR proved to be a promising technology for detecting and localising delamination in composites.

Composite bonded lap joints, which are an effective connecting method for composite constructions, are routinely monitored via optical fibres. Fatigue tests were performed using fibre-optic sensing devices as a potential method for monitoring such structures [141–143]. A single lap adhesively bonded CFRP joint was subjected to a 3.5 kN load with a test frequency of 10 Hz until failure at 60,000 cycles in the former. The optical fibre was bent such that it could monitor four segments on the front surface and two segments on the back surface with just one optical fibre. By halting the test every 5000 cycles, the measurements were taken at the mean load value. The whole strain profile and the minimum strain value were acquired from the OBR readings. From the FEA conducted, it was discovered that minimum strain and crack length had a linear relationship. Wong et al. [143] put a flush-step lap joint of CFRP through a fatigue test. One optical fibre was looped onto the surface and used to monitor the junction on both sides. An extensometer was used to determine the relationship between strain and load. With a frequency of 5 Hz, the specimen was subjected to a peak strain of 1000, which was increased to 2000 after 100,000 cycles. The test was carried out until it failed after 250,000 cycles. Increased strain values in the past 3500 cycles were indicative of damage prior to the breakdown. Optical fibre sensors have proven to be a promising approach for damage assessment and monitoring of fatigue crack propagation, with great potential for incorporation in structures for monitoring while in operation.

The research previously mentioned is primarily focused on lab experiments. The OBR was used to monitor real structures in Barcelona in a study by Barrias et al. [144] on the Sarajevo Bridge in Barcelona, Spain, which was monitored while it was being built without the bridge being closed to traffic. The goal was to detect changes in the bridge’s structural behaviour during and after construction, as well as to determine the bridge’s structural safety. In areas prone to stress increases and cracking, optical fibres were installed along the length of the bridge. The measurements were taken on two 50 m optical fibres. The monitoring took place over a nine-month period, with readings taken during certain monitoring periods. Temperature variations affect the behaviour of both the structure and the optical fibre over such a long monitoring period. This temperature effect has an impact on both the refractive index and the substance of the optical fibre. This can be mitigated by using point-to-point thermal compensation or loop-based thermal compensation. These compensating methods rely on a piece of optical fibre being unbonded in a tiny tube or loop. Thermal correction by loop was applied in this case. From the strain produced from the bonded portion, the strain depending on the refractive index and the strain dependent on the optical fibre’s thermal expansion are eliminated. The measurements revealed that the optical fibres were successfully installed. The OBR was successfully used in the model to obtain measurements over time. Finally, across a wide range of applications, OBR has provided satisfactory monitoring results. Experimental tests and finite element analysis are required to ensure that this is the best option for the specified application. Finding the most significant life-limiting factor for glass fibre composite repair and conducting tests accordingly is reasonable. Since the glass fibre composite bands employed for the repair can be woven, some voids and resin-rich areas can be expected surrounding the
optical fibres. As a result, measurements acquired using optical sensors may have more noise than the OBR's potential, and the running reference approach for strain analysis may be appropriate.

3. Methodology and Design Approach

This section presents the methodology and design approach proposed for composite risers.

3.1. Design Approaches

3.1.1. Design for Local Loading

The first design is a composite riser using similar designs for the layers, considering the number of layers and type of material, and the lay-up configuration. Since the composite riser is multi-layered and has a structure that is quite complex, the design is simplified by removing sophisticated cases, and stating all assumptions considered, such as that the manufacturing of the complex riser is a perfect CPR product. Additionally, since the design of the composite riser incorporates more variables, unlike the design of the steel riser, three stages were approached in the local design of the composite riser tube, starting with the geometry design. It is also noteworthy to add that the composite tube is made up of the liner material, the liner thickness, the layup configuration, the laminate arrangement, the composite layer thicknesses, and the subjected local loadings. The local design should first be performed to generate the first estimate of the laminate required, the composite body, its wall thickness, liner thickness, and the laminate configuration [27–31]. This can be obtained by considering different computations, such as composite theories, homogenisation, or the Netting theory [31–33]. If the forces and stresses on the composite body increase, the configuration and thicknesses of its liner and composite body can then be modified and redesigned. Additionally, if it led to some increase in moments acting across the lengthwise cross-section of the composite riser, then some structural reliability is required upon redesign. Under global loads, these moments can be determined by the large deformations to which they are subjected. These moments are also dependent on the cross-sectional tubular geometry of the composite riser. Note that these global loads can be computed using environmental weather conditions obtained from ocean monitoring as recorded in guidance bulletin [145]. On the other hand, the local design can be carried out by utilising layered solid elements in finite element analysis (FEA) to determine the stress distributions in each layer of the laminate with precision [23,27,34,146–148].

The design moves on to the second phase once the local geometry has been tentatively determined. In this stage, the entire riser is analysed under global stresses to evaluate its critical condition sites, as well as the load combinations that can be used at these locations. Pipe elements that are one-dimensional are used in FEA for global analysis, such as layering 3D elements over the whole surface. The third stage of the design is the structural verification of these main areas, which is defined by the global forces, pressures, and moments operating on them. A major design consideration will be the length of the riser. For instance, a 2000 m-long riser would be prohibitively very computationally expensive. Thus, a second 3 m or 5 m model can be considered in the local design to reduce computational resources and for ease of modelling.

3.1.2. Design for Global Loading

In this research, the composite riser was designed based on the criteria for extracting natural resources from a depth of approximately 2030 metres in the Gulf of Mexico (GoM) using the API RP2Int-Met standard [145]. In global design, two different design configurations are considered. This second design uses the global load and platform load on the marine riser. The type of marine riser configuration is also important, such as the TTR configuration attached to a SPAR platform, submarine hoses on floating buoys, and semisubmersible platform [149–151] with a metallic tension junction at the top and a metallic stress joint at the bottom, called the bottom joint. The first model recommended in the initial phase of the design is a steel riser, which is designed for minimum weight
requirements and as a base case design for benchmarking. The loading requirements include functional and environmental loads in both local and global cases in accordance with the respective industry specification(s). Figure 8 illustrates a floating structure with marine risers and mooring lines.

![Schematic showing marine risers and mooring lines on a floating platform. The green lines are steel catenary risers (SCR), the black dash straight lines are top-tensioned risers (TTR) while the red lines are mooring lines.](image)

Figure 8. Schematic showing marine risers and mooring lines on a floating platform. The green lines are steel catenary risers (SCR), the black dash straight lines are top-tensioned risers (TTR) while the red lines are mooring lines.

### 3.1.3. Design for End Fitting, Liners, and Metal–Composite Interface (MCI)

Since the riser would have a liner and an end fitting, as well as mid-joint sections that are metallic, there is a need to also investigate the effect of the metal–composite interface (MCI) in the design. The investigation was also carried out on the MCI with layered 3D elements to precisely determine the stress distributions on the composite riser tube, its liner, and its end fitting. For the end fitting design, four different end fitting models were considered, but one was chosen with justification based on its performance. Additionally, the results of the study were checked against the material limits. In the design, certain checks were made to ensure safety factors (S.F). Any of the design models with S.F that does not fulfil the design requirements would require the component being redesigned, as well as the complete design process being repeated. The design models that passed this requirement were presented.

Based on the liner considerations, there are different distinct material combinations to choose from, including high-strength and high-modulus materials. As for the composite tubular structure, the material specifications include metallic liner materials, thermoplastic/thermoset matrices, and fibre reinforcements. For the fibre reinforcements, carbon fibres and glass fibres were comparatively studied in this research.

### 3.1.4. Design for Optimisation

The composite riser must be modelled first, and then the design can be optimised later. There could be various composite material combinations. These designs can be developed to be as light as possible by utilising unique methodologies. These could be traditional (or conventional), local, and customised (or tailored) design techniques. The traditional design considers layout in axial and hoop directions without any off-axis directions. Only fibre is considered in this strategy, which has been used in many earlier projects [152–162]. However, the later strategy of the customised design includes reinforcements in the axial and hoop directions, and analyses those in other intermediate angles that are optimised for the smallest possible angle [163–173]. However, optimisation of composite riser design should be included in design guidelines. One challenge that is faced numerically is the computational resources and number of run times required to achieve a composite riser optimisation model. Detailed investigations on the weight of the composite structure, with some considerations for optimisation, have also been conducted [29–32]. In these studies, the three design methods have been applied, with some optimisation. Comparisons can
be made between the optimised model and the tailored model used to verify the design approaches and materials selected using different mathematical optimisation methods.

3.1.5. Design for Motion Response and Stability

The design of the motion response and stability of the composite risers was based on studies of their hydrodynamics and mechanics. A somewhat ‘flexible design approach’ can be considered by using a hybrid layered structure having composite layers. This makes it easier to incorporate the riser model into a floating platform and investigate its response based on the design of the motion and stability of the floating structure. In some aspects of ocean engineering research, the motion and stability of other structures, such as semisubmersibles, can also be examined, and incorporated with marine risers, mooring lines, and tensioners. However, further work on the composite riser by requiring new configurations led the direction of the research to consider the design. Engineering systems are designed and investigated using the requirements of industry standards. Depending on the application, the effect of different components, such as hawsers, mooring lines, and the motion offset, can also be looked at for further incorporation into design guidelines. In that case, different ocean and weather conditions were considered to obtain the wave spectra. For global design, weather conditions are used based on weather reports and real-time data. As seen in the typical parameters for the global design in Table 1 and Figure 9, different environmental conditions could be considered for designing composite risers. The selection for oceans, waves, and currents depends on the varying weather conditions around the world. Environmental data for global rising sea levels and global climatic weather conditions are available in Figures A3 and A4.

Table 1. Typical parameters for waves and environmental conditions.

| Case ID | Hs (m) | Tz (s) | Tp (s) | Conditions   |
|---------|--------|--------|--------|--------------|
| 1       | 2.60   | 6.20   | 7.95   | Operation    |
| 2       | 3.80   | 5.10   | 8.35   | Extreme      |
| 3       | 4.30   | 5.70   | 9.85   | Survival     |

Figure 9. Typical wave data on the JONSWAP spectra.
This data is necessary to ensure that the composite riser is safely designed and that the design can operate in deep water environments. It also enables an understanding of the effect of riser integration on the supporting structure and the level of motion response from the marine riser system across various regional seas. The effect of phenomena such as wave–current interactions and vortex-induced vibrations (VIV) can also be conducted, as illustrated in Figure 10.

**Figure 10.** Wave–current interaction and vortex-induced vibration and motion response on a floating buoy as a typical floating structure.

Numerical investigations can be conducted using the CFD model using ANSYS Fluent and Simscale’s OpenCFD to investigate the effect of drag coefficient, flow patterns around the floating buoy, vortex identification on the structure, and VIV on the riser. The designs for investigating wave–current interactions (WCI) can be carried out using hydrodynamic diffraction analysis in ANSYS AQWA. The wave parameters can be developed by utilising the flow’s potential theory. This represents the dynamics of the flow with a velocity potential that changes with time and distance. Using the flow potential, a calculation of the flow’s force parameters can be obtained. This eliminates the challenges related to the complexity of flow rotation and separation. The study of the VIV included system coupling from the ANSYS ACP into ANSYS Fluent, which can provide insight into the challenge from the vortex shedding effect on the composite riser [26,102].

### 3.1.6. Design for Weight Savings and Strengths

In the design of the composite riser, the aim is to reduce deck loads by having a novel composite riser that has light weight as well as strength. From some investigations, different composite riser models have been developed. There are diverse findings on the best combination, such as AS4/PEEK, as each design is relative to the requirements of this investigation, the design parameters, and the numerical model. Based on the global design, the wave, current, and wind loads can be extracted from the hydrodynamic analysis using numerical tools, such as WAMIT, ANSYS AQWA, ABAQUS AQUA, and Bentley’s Moses. This can be applied as the loading conditions in the FEM by coupling it into Orcaflex from ANSYS AQWA. The static loads include the buoyancy force acting upwards, the riser weight, the mooring weight, the weight of liquid stored in the columns, the load of the facilities, the operating loads, the topside weight, and the hull steel weight. The
results obtained from the FEM and CFD studies can be used to make some conclusions and recommendations on the following aspects:

- Laminate configuration;
- Design approach for weight savings;
- Laminate thicknesses;
- Liner design and materials to use;
- Nature of steel grade and the materials to use;
- Marine riser design;
- Composite tube design;
- End-fitting design;
- Recommendations for layer thicknesses;
- Marine hose and composite riser designs;
- Configurations for composite risers;
- Guidance on Dynamic Amplification Factor ($DAF_{hose}$);
- Recommendations for composite riser motion response; and
- VIV of composite risers and supporting structures.

3.2. Model Development

Based on the model development, there were five sets of numerical models recommended against different experimental models that can be developed to understand the behaviour of the composite riser based on its hydrodynamics and mechanics, with a response when attached to floating structures; these are:

- Composite model: This was set up to design the composite structure, such as a composite production riser (CPR), which can be modelled as a multi-layered structure with 18 layers with different configurations. Depending on the designer’s choice, it can be developed using different numeral tools, such as ABAQUS or COMSOL composite module or ANSYS ACP module, linked to ANSYS Static Structural, ANSYS Mechanical, and system coupled.

- Mechanical model: The mechanical model is a benchmark model of the steel riser used as a benchmark model. It was also used when modelling the metallic aspects of the composite structure. Using the case study of CPR, the mechanical model can be used to model its metallic liner.

- Finite element model: The finite element model (FEM) is developed to investigate the safety factors and stress magnitudes on the different layers of the composite riser under static load and dynamic load cases. In CPR studies, the FEM is also developed for the static loads in ANSYS Static Structural, Solidworks 2020, ANSYS Design Modeler, ANSYS ACP, and Orcaflex. The FEM can be used to investigate the strength of the CPR, the fatigue behaviour, the impact analysis, the tensile properties, and the deformation profile of the marine riser.

- CFD model: The flow around the marine riser can be investigated for vortex effects. This is usually conducted using a computation fluid dynamics (CFD) tool, such as ANSYS Fluent, ANSYS CFX, or COMSOL Multiphysics. The model is developed by considering the nonlinear drag parameter, flow around the floating buoy, and effect of strakes on the riser as modelled in this study. The CFD model can then be further developed in the later stage of the project to understand the nature of flow around the hull, such as a tension leg platform (TLP), Truss SPAR, or semisubmersible hull. It can also be conducted to understand the effect of flow around the riser, when risers are integrated into the floating structures, the effect of Vortex-Induced Vibrations (VIV), and the effect of strakes on the risers. The oscillation from the waves and drag effects on the structures are recorded, and reciprocating shed vortexes can be observed. Figure 11 shows a typical illustration of the flow pattern and vortex effect around the structure examined in the CFD study.

- Hydrodynamic model: Hydrodynamic aspects can be set up to investigate the motion response of the composite riser under wind, current, and wave loads. CPR can be
developed in WAMIT or ANSYS AQWA using the Boundary Element Method (BEM) using pipe elements and Morison elements. The AQWA model was also coupled with Orcaflex for the hydrodynamic model, as Orcaflex applies line theory. It is noteworthy to add that the hydrodynamic model can be developed using diffraction principles to characterise the motion behaviour of both the TTR composite riser and the composite submarine hose models. Current practice requires that they be modelled using the response from wind, wave, and current loads by considering industry standards and specifications. The Boundary Element Method (BEM) could be used to conduct this investigation in ANSY AQWA, as the BEM formulations are used in the AQWA package. The AQWA solver solves a set of complex partial differential equations describing the flow potential near the incidence, diffraction, and radiation boundaries. The force, pressure, and moment parameters can then be computed after resolving these sets of equations. A wave spectrum was used to study complex and irregular wave behaviour. The influence of drift second-order factors on the hull’s reaction behaviour in complicated wave flow was explored. Interactions between currents and waves should also be considered. The hull’s response can then be investigated under the time and frequency domains using the basic motion equation for a single degree of freedom (DoF) system, with multiple line matrices built to compute succeeding degrees of freedom. However, various software packages may produce different results, but they may be similar, depending on the study investigated when compared, and validated before use.

- **Experimental model:** Validation of the model should be conducted to ensure the validity and correctness of the hydrodynamic model. This can be achieved by experimental studies set up using a wave tank testing facility, such as the Lancaster University wave tank. The motion of the scaled-down risers will be attached to the hull models of a floating platform. Data are outputted during the experiment, which must be recorded. However, to ensure consistency in the design, different runs are required. The experimental results with the attached risers on the floating structure’s model can also be presented. However, there are also different approaches that could be applied in any experimental investigation. Figure 12 shows an experimental model in a wave tank.
different results, but they may be similar, depending on the study investigated when compared, and validated before use.

**Experimental model:** Validation of the model should be conducted to ensure the validity and correctness of the hydrodynamic model. This can be achieved by experimental studies set up using a wave tank testing facility, such as the Lancaster University wave tank. The motion of the scaled-down risers will be attached to the hull models of a floating platform. Data are outputted during the experiment, which must be recorded. However, to ensure consistency in the design, different runs are required. The experimental results with the attached risers on the floating structure’s model can also be presented. However, there are also different approaches that could be applied in any experimental investigation. Figure 12 shows an experimental model in a wave tank.

![Figure 12](image-url) An experimental model in the Lancaster University wave tank facility showing a floating buoy with wave gauges for monitoring the wave forms and position of the buoy.

### 3.3. Analysis Setup and Software Utilisation

During this research, the design of the composite risers involved a combination of various commercial and open-source software.

#### 3.3.1. Setup for Numerical Analysis

- For the FEM models, the numerical setup was developed in ANSYS Structural, Solid-works, ANSYS ACP. Others were on ANSYS APDL, ABAQUS, and Simscale OpenFEA.
- For CFD analysis, the numerical setup can be developed in ANSYS CFX, ANSYS FLUENT, COMSOL Multiphysics, and OpenCFD.
- For hydrodynamic diffraction and response analysis, the numerical setup can be developed in ANSYS AQWA and Orcina’s Orcaflex.
- The CAD models can be built in SolidWorks, ANSYS Design Modeller, and Autodesk Inventor.
- For the FSI (fluid–structure interaction), ANSYS Hydrodynamic and ANSYS Diffraction models can be used.
- A numerical setup for risers and mooring analysis can be developed in Orcaflex and ANSYS AQWA.

#### 3.3.2. Setup for Experimental Analysis

- Wave tank testing facility;
- Regular waves: sea state and sinusoidal wave;
- Imetrum System for DIC (Digital Image Capture);
- Electronic wave gauges;
- LabView Software;
- Edinburgh Designs wave tank software;
- WitMotion Bluetooth Sensors; and
- Akaso 4k Underwater Video Camera (see Figure 13).
Figure 13. The AKASO EK7000 camera utilised in the experiment with its part labelled. It is used to monitor the motion of water waves against the floating structure inside the wave tank or flume used.

### 3.3.3. Software for Modelling and Analysis

Different marine riser analysis software programmes can be applied to both riser-specific and general-purpose software packages currently available. Table 2 presents the most widely used marine riser software. The data were compared for institutional usage by comparing the software available in the authors’ affiliations as case studies using Lancaster University, UK and Universiti Teknologi PETRONAS, Malaysia at the time of this investigation, which were also applied in this research, as presented herein.

#### Table 2. Analysis Software for Marine Riser and related ocean engineering facilities.

| Software       | Vendor         | Approach               | Academic License Available at: | Popularity | Usage |
|----------------|----------------|------------------------|--------------------------------|------------|-------|
|                | Nonlinear FEM | Frequency Domain       | Time Domain                    | LancsUni   | UTP   |
| OrcaFlex       | ORCINA         | ✓                      | ✓                              | ✓          | ✓     | ****   | Wide   |
| ABAQUS         | SIMULIA        | ✓                      | ✓                              | ✓          | ✓     | ***     | Limited |
| ANSYS          | ANSYS          | ✓                      | ✓                              | ✓          | ✓     | ****    | Limited |
| DeepLines      | PRINCIPIA      | ✓                      | ✓                              | ✓          | ✓     | ***     | Limited |
| ANFLEX         | —              | ✓                      | ✓                              | ✓          | ✓     | ***     | Limited |
| Freecom        | MCS            | ✓                      | ✓                              | ✓          | ✓     | *       | Limited |
| Flexcom        | MCS            | ✓                      | ✓                              | ✓          | ✓     | **       | Limited |
| Riflex,        | MARINTEK       | ✓                      | ✓                              | ✓          | ✓     | ****    | Limited |
| Simscale       | SIMSCALE       | ✓                      | ✓                              | ✓          | ✓     | ***     | Limited |
| Sesam          | DNV            | ✓                      | ✓                              | ✓          | ✓     | ***     | Limited |
| OrcaLay        | Orcina         | ✓                      | ✓                              | ✓          | ✓     | ***     | Limited |
| Pipelay        | MCS            | ✓                      | ✓                              | ✓          | ✓     | ***     | Limited |
| Solidworks     | Dassault Syst. | ✓                      | ✓                              | ✓          | ✓     | ****    | Limited |
| Mathcad        | MATHSOFT       | ✓                      | ✓                              | ✓          | ✓     | ****    | Limited |
| MatLab         | MATHWORKS      | ✓                      | ✓                              | ✓          | ✓     | ***     | Limited |
| PVI            | Pegasus Vertex | ✓                      | ✓                              | ✓          | ✓     | *       | Limited |
| MOSES          | Bentley        | ✓                      | ✓                              | ✓          | ✓     | ****    | Limited |
| DeepC          | DNV            | ✓                      | ✓                              | ✓          | ✓     | ***     | Limited |
| Helica         | DNV            | ✓                      | ✓                              | ✓          | ✓     | *       | Limited |
| LabView        | National Instr. | ✓                      | ✓                              | ✓          | ✓     | ****    | Limited |
| PIPESIM        | Schlumberger   | ✓                      | ✓                              | ✓          | ✓     | *       | Limited |
| OLGA           | Schlumberger   | ✓                      | ✓                              | ✓          | ✓     | *       | Limited |
| Inventor       | Autodesk       | ✓                      | ✓                              | ✓          | ✓     | ***     | Limited |
| VIVANA         | DNV            | ✓                      | ✓                              | ✓          | ✓     | ***     | Limited |
| WAMIT          | WAMIT          | ✓                      | ✓                              | ✓          | ✓     | ***     | Limited |

(Note: Asterisk (*) is Author’s rating of software’s popularity and usage, **** is rated highest while * is the least).
3.4. Qualification and Standards Utilisation

During this research, some standards are recommended for designing, qualification, and monitoring composite risers, as discussed in this section.

3.4.1. Qualification

A component’s qualification certifies that the component’s structural integrity has been retained. Component management is a crucial aspect of the qualification process. Both theoretical assessments and verification by testing are carried out in accordance with relevant standards to qualify a structure. For qualification, the composite riser pipe must be tested thoroughly to ensure that it can perform during the in-service case [174–179]. For theoretical assessments, some numerical models or simple test cases may be provided, and the numerical models used must be well validated. Furthermore, the design, installation, and maintenance of the specific application must meet the requirements of industry standards and guidelines; otherwise, it will not be in service. After that, the most important standards are provided, along with a brief explanation of how they are qualified. It is important to make some observations on related industry standards for the qualification of composite risers.

DNV-RP-F202: Composite Risers

This standard provides the recommended practice for the application of composites to marine risers, though with some limitations. There is insufficient information on practical data, design limits, recommended composite materials, and global design investigations using a floating platform. However, it specifies very helpful guidance on the design of composite risers. The physical properties of the composite are modified when exposed to external conditions over a long period, such as a year, and the impacts usually increase over time. Due to their chemical differences, the fibre and matrix react differently to environmental circumstances. Environmental resistance is influenced by the fibre matrix interface, void content, and matrix cracks. Temperature, water, chemicals, and UV radiation are among the environmental factors considered by the standard. Seawater is said to have a milder effect than fresh water. The composite is influenced more severely by the combination of water and high temperatures than if the influences occurred separately.

DNV-GL OS C501: Composite Components

This standard outlines rules and guidelines for the design and analysis of composite components, as well as their modification, operation, and upgrading. It is applicable to all composites. The importance of environmental loads and circumstances in the offshore business is stressed, as well as factors such as paperwork, verification, and inspection. There are specifications for composite restorations that are predicated on reaching the same level of strength and functioning as the original construction. A composite repair is essentially a laminated joint, with the interface for load transfer being the most important component. Testing can be done to qualify a component or to confirm the accuracy of an analysis or design calculation. No failure will be critical for the component’s functionality or safety, according to testing and analysis. The evaluation of likely failure causes is critical for a particular application when long-term performance is required. The test specimens must be accurate representations of the component in question. Only the load situations and environmental circumstances examined are valid for the test findings. The failure mode(s), failure mechanism(s), and failure location(s) must all be documented and validated.

ASME PCC-2-2015: Repair of Pressure Equipment and Piping

During the service life of equipment and pipelines, this standard defines how to design, construct, evaluate, and test repairs. This standard is primarily intended for broad applications and may not be appropriate for everyone. Testing is required to determine mechanical and thermal parameters, such as tensile strength, in-plane shear modulus,
lap shear adhesion strength, and thermal expansion. A minimum value (if applicable) is specified, as well as which test method applies to which property.

**DNV-RP-C301: Design, Fabrication, Operation, and Qualification on Bonded Repair of Steel Structures**

For bonded repairs, this paper outlines rules and recognized techniques. Chemical and thermal loads may hasten the breakdown of such repairs, which are sensitive to environmental stressors. Non-destructive inspection (NDI) technologies, such as ultrasound and x-ray, are recommended for detecting laminate delamination. However, no technology is recommended for detecting bondline faults. If the repair is to be exposed to thermal fatigue, long-term tests are required to establish the effects of thermal loadings. It is pertinent that there should be proper documentation of the long-term tests, ultrasound tests, x-ray tests, and other non-destruction inspection reports.

**DNV-RP-A203: New Technology Qualification**

This best practice outlines a method for systematically qualifying new components, equipment, and assemblies that use new technology, mostly for offshore applications. Furthermore, qualified technology in a novel location or previously qualified components integrated in a novel manner are both considered innovative technologies. There are five steps in the qualification procedure. The qualification basis is developed first, followed by the qualification requirements. The technology is also evaluated, with obstacles and uncertainties noted. Threats are assessed, and failure modes are identified based on the level of criticality which is determined by the risk to the components as well as the system. The activities necessary for the qualification are then designed, completed, and documented.

### 3.4.2. Standard Utilisation

In research, one of the findings is that there are limited standards for composite risers [106,107,174]. The limitation of the application of composite risers includes the elaboration of these standards, which is not considered in this study, but recommendations were made on standards for composite marine risers. Other issues that were not looked at are reliability analysis, and health and safety issues. In addition, some tasks require special codes to obtain some results and to develop new codes/programs to obtain the desired results. Additionally, several industry standards are utilized on marine risers, as there are limited standards specific to composite risers, as shown in Table 3. These are some recommendations, guidance reports, and industry standards related to composite risers, marine risers, and floating structures that can be considered at different stages.

**Table 3.** Industry Standards, Codes and Guidelines on marine hoses, flexible pipes and composite marine risers.

| Ref. No. for Standards | Titles and Description |
|------------------------|------------------------|
| DNV-OS-F101: 2013      | DNV Offshore Standard: Subsea Pipeline Systems |
| ABS 2017               | Guide for Building and Classing subsea riser systems. 3rd ed. |
| DNV-RP-F202: 2010      | DNV Recommended Practice: Composite Risers |
| DNV-OS-F501: 2013, 2010| DNV Recommended Practice: Composite Components |
| API 2INT-MET; 2007     | Interim Guidance on Hurricane Conditions in the Gulf of Mexico |
| API Bulletin 16        | Bulletin on Comparison of Marine Drilling Riser Analyses |
| API RP 17G; 2011; 2nd Ed. | Recommended Practice for Completion/Workover Risers, |
| API 17J; 2013          | Specification for unbonded flexible pipe |
| API 17K, 2017          | Specification for bonded flexible pipe |
| API 15S; 2013          | Qualification of spoolable reinforced plastic line pipe |
| API RP 2Q, 1984        | Recommended practice for design and operation of marine drilling riser systems (Been Replaced) |
| API RP 16Q, 2010       | Design, selection, operation and maintenance of marine drilling riser systems (To Replace API RP 2Q) |
| ASTM D4762; 2011       | Standard guide for testing polymer matrix composite materials |
Table 3. Cont.

| Ref. No. for Standards | Titles and Description |
|-----------------------|------------------------|
| API-RP-2RD 2009       | Design of Risers for FPSs and TLPs (errata Ed.) |
| DNV-OS-S-302; 2010    | DNV Service Specification: Offshore Riser Systems |
| DNV-OS-F201; 2010     | DNV Offshore Standard: Dynamic Risers |
| DNV-RP-F201; 2010     | DNV Recommended Practice: Design of Titanium Risers |
| BS 7910:2013          | Guide to methods for assessing the acceptability of flaws in metallic structures |
| DNV-RP-F203; 2010     | DNV Recommended Practice: Riser Interference |
| DNV-RP-F204; 2010     | DNV Recommended Practice: Riser Fatigue |
| DNV RP C203; 2008     | Riser Integrity Management: Recommended Practice |
| DNV RP C203; 2007     | Environmental conditions and Environmental loads |
| DNVGL-RP-A203, DNV RP C203 | Technology Qualification: Recommended Practice |
| DNV Tech. Rep. 2002-0067 | DNV Project recommended practice: composite risers, Technical Report Rev. 5 |
| DNVGL-CG-0170; 2015   | Offshore classification projects—testing and commissioning (To Replace DNV-RP-A205: 2015) |
| DNVGL-RP-F119; 2015   | Recommended practice: Thermoplastic composite pipes (TCP) |
| ISO 13624-1: 2009     | Part 1: Design and operation of marine drilling riser equipment |
| ISO 13624-2: 2009     | Part 2: Deep water drilling riser methodologies, operations, and integrity (technical report) |
| ISO 13625: 2002       | Marine drilling riser couplings |
| ISO 13628-7: 2010     | Completion/workover riser system |
| ISO 13628-10: 2005    | Part 10: Specification for bonded flexible pipe |
| ISO 13628-11: 2007    | Part 11: Flexible pipe systems for subsea and marine applications |
| MMS Riser Guide; 2010 | Composite Riser Experience and Design Guidance -Ochoa |
| RPSEA 1101496; 2014   | Riser Concept Analysis and Recommendation Report |
| NORSOK M-001; 2002    | Norsok Materials Selection Standard |

4. Application and Case Study Analysis

The application of monitoring on advanced composites requires some discussion of its advantages, developments, and analysis of some case studies, as presented in this section.

4.1. Application of Advanced Composites

The composites industry appears to be waiting for “the big one”—the game-changing application that will drive composites into the mainstream of materials. Offshore oil has been identified as one such area with such potential. Composites have been gradually replacing topside (above water level) metal in a growing number of offshore facilities, in both new installations and retrofits of existing structures, for some time. However, large-scale applications, such as carbon composite riser pipes for deepwater drilling, are on the verge of commercial success, bringing the market very close to “big one” status for the first time. Composites have a significantly lower weight and far stronger corrosion resistance than traditional offshore materials, and regulatory and materials-certification organisations are increasingly accepting composites. Weight reduction is a primary driver since lighter structures cost less to construct and allow for more drill pipe and oil production equipment. “When installed costs are examined, the cost gap narrows, and when life-cycle costs are evaluated, the cost differential swings in favour of composites” [180]. Fibre-reinforced plastic pipes have been shown to save up to 70% during their lifetime. When manufactured with chemical-resistant resins, composites are almost corrosion free, unlike steel, which corrodes quickly in seawater. This corrosion resistance translates to years of maintenance-free service for platform components, such as column pipes (pipes that extend from the platform down below the water surface to provide seawater) and firewater systems (strategically located pipes for combating potential fires). Steel pipe installations are sometimes severely rusted after only two or three years of service, according to one
Gulf Coast manufacturing factory, but thousands of composite column pipes are still in use, some of which are more than 25 years old.

Composites have also benefited from key regulatory changes in the last five years. On offshore platforms and drill ships, the US Coast Guard allowed the use of fibre-reinforced polymer (FRP) pipework and glass/phenolic gratings in late 1998, as given in USCG Policy File Memoranda (PFM) 1–98 and 2–98 [180–183]. The International Maritime Organisation (IMO) has certified composite pipes for use in water-carrying platform fire-fighting systems, as required by the IMO’s Level 3 Fire Endurance requirements (A.753), which include jet fire endurance criteria. (“Jet fire” refers to the high-pressure emission of burning hydrocarbons). However, IMO standards prohibit the use of composite pipes for flammable liquids, such as hydrocarbons or diesel fuel (Level 1 Fire Endurance), making certification doubtful. For composite piping applications, ISO 14692 (International Organization for Standardization) proposes a performance-based risk assessment. Det Norske Veritas, a Norwegian certification company for seagoing vessels and structures, later released two composites’ standards: DNV-OS-C501 and DNV-RP-F202. DNV-OS-C501 is an offshore standard that specifies the requirements and methods for composite component structural design and structural analysis. On the other hand, DNV-RP-F202 is the Recommended Practice that prescribes performance-based guidelines for composite riser certification. Both point to a rising acceptance of composites in the design and construction of offshore oil platforms.

4.2. Advantages of Advanced Composites

Composites are becoming increasingly used in the oil and gas industry. Despite all the advantages of composites, the oil and gas industry has been slow to adopt composite solutions. This is sometimes linked to the industry’s old guard’s conservatism, which believes that steel is “good enough” to suit its needs. Another significant issue confronting composites is the lack of a universal design and qualification standard. Hence, this review on the monitoring of composite risers has been conducted by presenting some design approaches, and recommended standards. While composites are making advances into retrofitting older platforms, simple material substitution for immediate weight reductions or corrosion resistance does not fully harness the advantages of composites. However, with retrofitting, these potential benefits can be obtained from composites. During the design stage, composites will be key to lowering total platform system costs. In addition, platform engineers have a strong incentive to design with composites in mind, given the wide range of proven composite solutions now accessible. Despite all the advantages of composites, the oil and gas industry has been slow to adopt composite solutions. This is sometimes linked to the industry’s old guard’s conservatism, which believes that steel is “good enough” to suit its needs. Another significant issue confronting composites is the lack of a universal design and qualification standard. A minimum testing duration of more than a year and a half is necessary under the current requirements for a new composite pipeline product. Material testing centres assist in the development of non-metallic field application technologies that are ready to use. By strengthening existing qualifications and developing new service standards, inspections, and monitoring systems, the goal is to promote composite use. Composites also have huge potential for use in pipe systems, risers, umbilical and frac plugs, and balls used during hydraulic fracturing. There is a scarcity of meaningful performance data to contend with, especially in harsh offshore locations, which is a key impediment to composites’ progress. However, the advantages of composite materials exceed the dangers associated with novel material technology.

Another advantage is that composite piping saves weight and costs on the top side. Some forms of topside facility pipework use composites as standard equipment. Composite pipes may now be constructed to withstand even the most intense jet fire conditions using phenolic resins, fire-retardant additives, and intumescent coatings. While conventional fibreglass composite pipes are non-conductive, there is significant debate in the industry about whether conductivity is necessary on a platform’s open deck. Most manufacturers
offer electrically conductive versions of their plumbing products for areas where operators want or demand them [180]. Composites are quite less pricey than the copper/nickel alloy commonly used for fire pipes. Composites have also been recorded as having the ability to be fabricated into fewer parts to fit into irregularly—shaped or sleek sections. Composite piping’s lower modulus allows for elasticity and flexibility in designs that would be impossible with a more rigid metal. Furthermore, bonded joints avoid the requirement for hot welding, which might be a fire hazard on a platform containing flammable hydrocarbons. Since composites can be ruined if dropped or struck by a large object, they must be treated differently than metal during installation.

4.3. Patent Publications

In the research on the guidelines for composite risers, patent publications for composite riser design are presented to discuss some developments made so far. These developments also show that some devices, apparatuses, and methods have also been patented on flexible risers and composite risers, which will aid in developing guidelines for composite risers. One particular standard that stands out is US20050100414 (also filed as CA2541542 and WO2005047641), whereby the system monitors the degradation of a composite riser string and ensures that its structural integrity is maintained. Composite riser structures with strain and vibration sensors are used in the system to assess variations in stiffness strain in the first and second orientations. Monitoring modules attached to each individual riser, as well as devices to convey data from the monitoring module to the surface controller, can be included in the system, as illustrated in Figure 14. When predetermined warning limits surpass, the monitor system can also sound an alert. Tables 4 and 5 present some patents on monitoring devices and methods, with some of these related components for composite risers.

Figure 14. Illustration of the monitoring module attached to the surface controller in the patent for composite riser monitoring devices and methods (Patent No.: US20050100414, Courtesy: Conoco Phillips Company).
## Table 4. Patent list for innovations in monitoring devices with methods for composite risers and steel risers.

| Patent No.                     | Reference                          | Date              | Title of Patent                                                                 |
|-------------------------------|------------------------------------|-------------------|---------------------------------------------------------------------------------|
| US20040206187A1               | Jerry Williams                     | 2 October 2007    | Performance monitoring of offshore petroleum risers using optical strain sensors |
| US2005010441A4                | Salama, Mamdouh M.                 | 12 May 2005       | Composite Riser with Integrity Monitoring Apparatus and Method                   |
| WO2005047641A1                | Conocophillips Company             | 26 May 2005       | Composite Riser with Integrity Monitoring Apparatus and Method                   |
| US20040177681A1               | Harthorn Larry K.                  | 16 September 2004 | Internal riser inspection device and methods of using same                       |
| US20050075846A1               | Hyeung-Yun Kim                     | 7 April 2005      | Methods for monitoring structural health conditions                              |
| WO2004111605A3                | Exxonmobil Upstream Res Co         | 20 October 2005   | Method and apparatus for fluid flow testing                                     |
| US20060045408A1               | Jones Martin P W                   | 2 March 2006      | Structural member bend radius and shape sensor and measurement apparatus         |
| US20060065401A1               | John Allen                         | 30 March 2006     | System for sensing riser motion                                                  |
| WO2006102259A2                | Shell Int’l. Research              | 28 September 2006 | Underwater structure monitoring systems and methods                              |
| US7194913B2                   | Shell Oil Company                  | 27 March 2007     | Methods and methods for monitoring stress in steel catenary risers              |
| US20060287942A1               | Advanced Structure Monitoring, Inc.| 21 December 2006  | Methods of networking interrogation devices for structural conditions            |
| US2007012111A1                | Advanced Structure Monitoring, Inc.| 18 January 2007   | Interrogation network patches for active monitoring of structural health conditions |
| US20070112515A1               | Gauthier Leo R Jr                  | 17 May 2007       | Light-speed hitpoint sensor                                                     |
| US20070266788A1               | Hyeung-Yun Kim                     | 22 November 2007  | Diagnostic systems of optical fiber coil sensors for structural health monitoring |
| WO2008020240A1                | Insensys Limited                   | 21 February 2008  | Fibre optic sensors                                                             |
| US2008014883A1                | Hyeung-Yun Kim                     | 26 June 2008      | Gas tank having usage monitoring system                                          |
| US7536912B2                   | Hyeung-Yun Kim                     | 26 May 2009       | Flexible diagnostic patches for structural health monitoring                    |
| US2009015738A1                | Hyeung-Yun Kim                     | 18 June 2009      | System for diagnosing and monitoring structural health conditions                |
| WO2009087371A1                | Services Petroliers Schlumberger   | 16 July 2009      | Monitoring system for pipelines or risers in floating production installations   |
| US20040206187A1               | Jerry Williams                     | 21 October 2004   | Performance monitoring of offshore petroleum risers using optical strain sensors |
| US10488296B2                  | Axel Sundermann                    | 26 November 2019  | Method of determining stress variations over time in an undersea pipe for transporting fluids |
| US20060233485A1               | Donald Allen                       | 19 October 2006   | Underwater structure monitoring systems and methods                              |
| US7461561B2                   | Denby Grey Morrison, Jeremy R. Dean| 9 December 2008   | Apparatuses and methods for monitoring stress in steel catenary risers          |
| US6999641B2                   | Jerry Gene Williams, David Barton Smith, Jeffrey David Muhs | 14 February 2006 | Measurement of large strains in ropes using plastic optical fibers             |
| US7781725B2; US20050082467A1  | Guy E. Mossman                    | 24 August 2010; 21 April 2005 | Optical fiber based sensor system suitable for monitoring remote aqueous infiltration |
| US8520195B2                   | Ramos R.T., Strong A., Lees G.     | 27 August 2013    | Method and system for estimating fluid leak flow rates using distributed optical fiber sensors |
| AU2006236751A1                | Rambow F.H.K.                      | 26 October 2006   | Method of applying a strain sensor to a cylindrical structure                    |
| US7245791B2                   | Rambow F.H.K., Dria D.E., Shuck M.Y.| 17 July 2007    | Compaction monitoring system                                                    |
| WO2012136259A1                | Fabien Ravet                       | 11 October 2012   | Method and assembly for sensing permanent deformation of a structure            |
| WO1993025866A1                | Edward Eduardovich Tapanes         | 23 December 1993  | Sensing patches utilising incorporated waveguide sensor                          |
Table 5. Patent list on monitoring devices with methods for composite risers, marine hoses, and flexible pipes.

| Patent No.       | Reference                              | Date               | Title of Patent                                                                 |
|------------------|----------------------------------------|--------------------|---------------------------------------------------------------------------------|
| US9915579B1      | David V. Brower                        | 13 March 2018      | Apparatus, system and sensor housing assembly utilizing fiber optic sensors for enabling monitoring operating conditions within a structural member |
| US9719309B2      | David V. Brower                        | 1 August 2017      | Instrumented strakes and fairings for subsea riser and pipeline monitoring       |
| WO2005064300A1   | Magne S., Ferdinand P., Pierre-Jean Daniel | 14 July 2005      | Instrumented tubular device for the transport of a pressurised fluid using bragg grating rosettes |
| US7703331B2      | Magne S., Ferdinand P., Pierre-Jean Daniel | 13 December 2007  | Instrumented tubular device for transporting a pressurized fluid                 |
| US10054516B2     | USA & NASA                             | 21 August 2018     | System and method for optical frequency domain reflectometer                      |
| US9250120B2      | Russell James Smith, Andrew Strong, Gareth P Lees | 2 February 2016    | Fiber-optic monitoring cable                                                     |
| US8973434B2      | Shell Oil Company                      | 10 March 2015      | Monitoring system for well casing                                                |
| US9927263B2      | The Penn State Research Foundation     | 27 March 2018      | Intrusion detection system for an undersea environment                            |
| US8789585B2      | Schlumberger Tech. Co.                 | 29 July 2014       | Cable monitoring in coiled tubing                                                |
| US20180136017A1  | Lloyd’s Register Americas, Inc.        | 17 May 2018        | Integration of fiber optic sensors into sleeve                                    |
| GB2522709A       | Aquaterra Energy Ltd.                  | 5 August 2015      | An offshore pipe monitoring system                                               |
| US6913079B2      | Paulo S. Tubel                         | 5 July 2005        | Method and system for monitoring smart structures utilizing distributed optical sensors |
| US5182779A       | Ltv Aerospace and Defense Company      | 26 January 1993    | Device, system and process for detecting tensile loads on a rope having an optical fiber incorporated therein |
| US6865194B1      | Cidra Corporation                      | 8 March 2005       | Strain-isolated Bragg grating temperature sensor                                 |
| EP2128571B1      | Daniele InaudiMarco BossiAntonio Barletta | 23 July 2014     | Fiberoptic strain sensor with distributed strain coupling                          |
| US20110088910A1  | Mccann Dominic                         | 21 April 2011      | Monitoring system for pipelines or risers in floating production installations     |
| US10168253B2     | Liu S., Guzzo J.A., Carbone J.W., et al. | 1 January 2019    | Marine riser management system including subsea acoustic monitoring platform and an associated method |
| US7793726B2      | Jeremiah DanielJames E. DaileyRuxin Song | 14 September 2010  | Marine riser system                                                               |
| US5908049A       | Williams, J.G., Sas-Jaworsky, A.,      | 1 June 1999        | Spoolable composite tubular member with energy conductors.                        |
| WO2013037002A1   | Woodside Energy Tech.                  | 21 March 2013      | Redeployable subsea manifold-riser system                                         |
| US9784041B2      | National Oilwell Varco                 | 10 October 2017    | Drilling rig riser identification apparatus                                       |
| US7798233B2      | Chevron U.S.A. Inc.                    | 21 September 2010  | Overpressure protection device                                                    |
| US3769127A       | Goldsworthy W., Hardesty E.            | 20 October 1973    | Method and apparatus for producing filament reinforced tubular products on a continuous basis. |
| US5520422A       | Ralph Friedrich, Ming Kuo, Kevin Smyth | 24 October 1994    | High-pressure fiber reinforced composite pipe joint                               |
| US8656961B2      | Chen, B.                               | 25 February 2014   | Composite flexible pipe and method of manufacture.                                |
4.4. Policy Implications and Recommendations

In recent years, hybrid flexible composite risers have become more adaptable. Currently, flexible risers have proven to be one of the most popular riser solutions for various floating production systems in shallow to deepwater in many parts of the world due to their good dynamic behaviour and dependability. The flexible pipe is made up of numerous layers of plastic and steel. The weight of the riser is supported by a huge number of steel wires (known as tensile armours) that are critical to the pipe’s integrity. As a result, it is critical to be able to guarantee the integrity of those armour wires and to notice a potential failure early enough to respond. Some innovative monitoring methods, such as FBG, as applied in Figure 15, are based on a clamped composite structure with embedded optical fibre. They track permanent deformation (torsion and elongation) and deliver cross-referenced data to improve integrity assurance dependability.

![Figure 15. Application of fiber optic sensor with an optical strain gauge in the corroded part of a pipe (Reprinted/adapted with permission from Dr. Chris Alexander; Source: Ref. [63]. Copyright year: 2018, copyright owner’s name: ASME & Dr. Chris Alexander).](image)

Even though armour layers are critical to the structural integrity of flexible risers, operators, and service providers around the world are still looking for reliable inspection or monitoring techniques that can detect the presence of cracks or other defects in the metallic wires that make up the pipe’s internal and external armour layers. Some advice on monitoring systems based on acoustic emission, residual magnetic field measurement, optical sensing, or the use of visual monitoring cameras has been provided in the literature [184–187]. So far, technology that relies on optical fibre sensors has yielded the best results. The use of fibre Bragg grating sensors to directly measure strains in each wire of the external traction layer provides an accurate and reliable real-time, continuous monitoring...
technique, giving the operator valuable information and an early warning if any deviation from the expected wire’s structural behaviour is detected.

In addition, since flexible pipes could have relative issues, repairs could be achieved with composite repair technologies, such as ComposiSleeve™, can be used on composite risers and other composite pipes [63,188–191]. Alexander et al. [63] recently presented an experimental investigation of the success of this repair regime using FBG sensors. Hence, composite tubes could also be repaired better by adequate monitoring and inspection of the onshore/offshore faults. In practice, monitoring provides a good alternative to standard maintenance methods because they may not always require shutting down operations [10]. A typical composite pipe repair system is shown in Figure 15.

Considering the technology applied in Figure 16, the sensors are placed on the area to be repaired and glued to it strategically, and then one end of the sensor is carefully linked to a wire onto a readout to obtain the readings after calibration. These composite riser repair systems have been developed using different techniques over time and have proven to be more effective under adequate monitoring [61–63]. The current repair practice considered for pipelines is the ANSI/ASME PCC-2 (ASME 2015); however, it is suggested to elaborate on the guidelines for composite riser repair. Figure 17 shows a typical composite pipe repaired using the ComposiSleeve™ sample, with the results shown in Figure 15.

**Figure 16.** Typical composite pipe repaired with ComposiSleeve™ sample (Reprinted/adapted with permission from Dr. Chris Alexander; Source: Ref. [63]. Copyright year: 2018, copyright owner’s name: ASME & Dr. Chris Alexander).
5. Conclusions

The study proposes some guidelines for composite risers, with some design approaches and monitoring techniques. For the design, six different considerations are presented for the composite flexible riser. For monitoring, four different techniques are identified; however, more monitoring techniques are available. However, the following conclusions are drawn from this study:

1. The future of monitoring and leak detection is promising, with possible combinations of different technologies examined to provide the best available solution and optimum environmental protection.
2. This study has identified a knowledge gap in the standards for composite riser technology and aids in closing it. In addition, this study presents important advances made on composite flexible risers and related monitoring devices through published patents.
3. In comparison to other industries, such as aerospace, automotive, and construction, where composites have been widely utilised for decades, the oil and gas industry has been sluggish to adopt them. On composite risers, the study explains the technology and design approaches that are advised.
4. This study provides some guidelines for designing and monitoring composite flexible risers. The study also presents software, specifications, and guidelines that should be considered in designing the composite structure. It also proposes some design approaches as guidelines that are advised, with some policy implications.
5. This study presents characteristics of the monitoring techniques of composite flexible riser technology. The advantages of the monitoring techniques include aiding composite riser measurements, recording data from riser deformation, improving integrity assurance, and dependability of design from stable readings.

6. Composites could be used for hybrid systems as composite flexible risers and to repair offshore faults, as they are a good alternative to standard maintenance methods.

Author Contributions: Conceptualisation, C.V.A.; methodology, C.V.A. and A.R.; software, C.V.A., A.R., I.A.J., C.A. and C.W.; validation, C.V.A. and A.R.; formal analysis, C.V.A., A.R., I.A.J., C.A. and C.W.; investigation, C.V.A., A.R., I.A.J. and C.W.; resources, C.V.A. and A.R.; writing—original draft preparation, C.V.A.; writing—reviewing draft, C.V.A., A.R., I.A.J., C.A. and C.W.; data curation, C.V.A. and A.R.; visualisation, C.V.A., A.R., I.A.J., C.A. and C.W.; supervision, C.V.A.; project administration, C.V.A., A.R., I.A.J., C.A. and C.W.; funding acquisition, C.V.A. and A.R. All authors have read and agreed to the published version of the manuscript.

Funding: The Engineering and Physical Sciences Research Council (EPSRC)’s Doctoral Training Centre (DTC), UK, and the Department of Engineering, Lancaster University, UK, are highly appreciated. Additionally, Niger Delta Development Commission (NDDC), Nigeria, is also appreciated for funding via the Overseas Postgraduate Scholarship. The authors also recognise the support of the Standards Organisation of Nigeria (SON), F.C.T Abuja, Nigeria.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data for this study is not shared as it is an aspect of an on-going study on this present research.

Acknowledgments: The authors also acknowledge the permissions of different publishers and industry firms on the images used in this publication. The authors acknowledge the technical support from Lancaster University Engineering Department. The permission from Chris Alexander to use some images in this manuscript is also well appreciated.

Conflicts of Interest: The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results. The authors declare no conflict of interest.

Abbreviations

3D Three-Dimensional
API American Petroleum Institute
ASME American Society of Mechanical Engineers
BEM Boundary Element Method
CFD Computational Fluid Dynamics
DNV Det Norske Veritas
CAD Computer-Aided Design
CFRP Carbon Fibre Reinforced Polymer
CPR Composite Production Riser
CRA Corrosion Resistant Alloy
DFOS Distributed Fibre Optic Sensors
DIC Digital Image Capture
DoF Degree of Freedom
DTS Distributed Temperature Sensing
ECA Engineering Critical Assessment
FBG Fibre Optics Bragg Gratings
FEA Finite Element Analysis
FEM Finite Element Model
| Abbreviation | Full Form |
|--------------|-----------|
| FOS          | Fibre Optic Sensors |
| FRP          | Fibre-Reinforced Polymer |
| GOM          | Gulf of Mexico |
| HFP          | Hybrid Flexible Pipe |
| IMO          | International Maritime Organisation |
| ISO          | International Organization for Standardization |
| IQI          | Image Quality Indicators |
| JONSWAP      | Joint North Sea Wave Project |
| LancsUni     | Lancaster University |
| MCI          | Metal–Composite Interface |
| NASA         | National Aeronautics and Space Administration |
| NDI          | Non-Destructive Inspection |
| NDT          | Non-Destructive Testing |
| NTNU         | Norwegian University of Science and Technology |
| OBR          | Optical Backscatter Reflectometer |
| OTDR         | Optical Time Domain Reflectometry |
| PFM          | Policy File Memoranda |
| PVDF         | Polyvinylidene Difluoride |
| RIM          | Riser Integrity Management |
| ROV          | Remotely Operated Vehicle |
| SCR          | Steel Catenary Risers |
| S.F          | Safety Factors |
| SHM          | Structural Health Monitoring |
| SPAR         | Single Point Anchor Reservoir |
| SURF         | Subsea Cables, Umbilicals, Risers, And Flowlines |
| TCP          | Thermoplastic Composite Pipes |
| TLP          | Tension Leg Platform |
| TTR          | Top Tension Riser |
| USA          | United States of America |
| UTP          | Universiti Teknologi PETRONAS |
| VIV          | Vortex Induced Vibration |
| WCI          | Wave–Current Interactions |
Figure A1. Map of all the ships showing their real-time positions globally at sea, with data obtained through monitoring (MarineTraffic.com, accessed on 23 November 2017).
Figure A2. Map of all the ships showing their real-time positions globally at sea, with data obtained through monitoring (MarineTraffic.com, accessed on 5 June 2022).
Figure A3. Map of sea level rising conditions globally and extreme weather (Courtesy: Mapsofworld).
Figure A4. Map of global climatic weather conditions showing the climate across different geographical zones.
References

1. Williams, J.G. Offshore Oil Composites: Designing in Cost Savings. Composites World, 26 February 2009; Issue 2. Available online: https://www.compositesworld.com/articles/offshore-oil-composites-designing-in-cost-savings (accessed on 11 May 2022).

2. Williams, J.G. Composite Material Offshore Corrosion Solutions. In Proceedings of the International Workshop on Corrosion Control of Marine Structures and Pipelines, Galveston, TX, USA, 9–11 February 1999. Available online: https://www.bsee.gov/sites/bsee/files/technical-assessment-program/392aa.pdf (accessed on 12 May 2022).

3. Reda, A.; McKee, K.K.; Howard, I.M.; Sultan, I.A. When is a subsea anchor required for a short pipeline/SCR system? Int. J. Pres. Ves. Pip. 2019, 171, 278–298. [CrossRef]

4. Reda, A.; Rawlinson, A.; Sultan, I.A.; Elgazzar, M.A.; Howard, I.M. Guidelines for safe cable crossing over a pipeline. Appl. Ocean Res. 2020, 102, 102284. [CrossRef]

5. Amaechi, C.V.; Chesterton, C.; Butler, H.O.; Wang, F.; Ye, J. Review on the design and mechanics of bonded marine hoses for Catenary Anchor Leg Mooring (CALM) buoys. Ocean Eng. 2021, 242, 110062. [CrossRef]

6. Amaechi, C.V.; Chesterton, C.; Butler, H.O.; Wang, F.; Ye, J. An Overview on Bonded Marine Hoses for sustainable fluid transfer and (un)loading operations via Floating Offshore Structures (FOS). J. Mar. Sci. Eng. 2021, 9, 1236. [CrossRef]

7. Diaz-Maroto, P.F. Structural Health Monitoring in Aeronautical Structures by Means of Distributed Fibre Optic Sensing Networks. Ph.D. Thesis, School of Aeronautical and Space Engineering, Polytechnic University of Madrid, Madrid, Spain, 2018. Available online: https://oa.upm.es/53147/1/PATRICIA_FERNANDEZ_DIAZ_MAROTO.pdf (accessed on 28 June 2022).

8. Bai, Y.; Bai, Q. Subsea Pipeline and Risers; Elsevier Publishers: Oxford, UK, 2005.

9. Kyriakides, S.; Corona, E. Mechanics of Offshore Pipelines: Volume I: Buckling and Collapse; Elsevier Publishers: Oxford, UK, 2007.

10. Lamviki, K.S. Monitoring of Composite Repair on Risers. Master’s Thesis, Norwegian University of Science and Technology (NTNU), Department of Mechanical and Industrial Engineering, Trondheim, Norway, June 2019. Available online: https://ntnuopen.ntnu.no/ntnu-xmlui/bitstream/handle/11250/2623204/no.ntnu%3ainspera%3A2525072.pdf?sequence=1&isAllowed=y (accessed on 1 June 2022).

11. Clarke, T.; Jacques, R.; Bisognin, A.; Camerini, C.; Damasceno, S.; Strohaecker, T. Monitoring the structural integrity of a flexible riser during a full-scale fatigue test. Eng. Struct. 2011, 33, 1181–1186. [CrossRef]

12. Woo, J.; Kim, D.; Na, W.-B. Damage assessment of a tunnel-type structure to protect submarine power cables during anchor collisions. Mar. Struct. 2015, 44, 19–42. [CrossRef]

13. Jie, W.; Yao-Tian, F. Study on Safety Monitoring System for Submarine Power Cable on the Basis of AIS and Radar Technology. Phys. Procedia 2012, 24, 961–965. [CrossRef]

14. Reda, A.; Abu-Siada, A.; Howard, I.M.; McKee, K.K. A testing platform for subsea power cable deployment. Eng. Fail. Anal. 2018, 96, 142–157. [CrossRef]

15. Nimmo, B.; Hinds, G. Beginners Guide to Corrosion; NPL: Teddington, UK, 2003.

16. Setvati, M.R.; Mustaffa, Z.; Shafiq, N.; Syed, Z.I. A Review on Composite Materials for Offshore Structures. In Proceedings of the ASME 2014 33rd Int. Conference on Ocean, Offshore Mechanics and Arctic Engineering, San Francisco, CA, USA, 8–13 June 2014; ASME: New York, NY, USA, 2014; Volume 5. [CrossRef]

17. Reda, A.; Howard, I.M.; Forbes, G.L.; Sultan, I.A.; McKee, K.K. Design and installation of subsea cable, pipeline and umbilical crossing interfaces. Eng. Fail. Anal. 2017, 81, 193–203. [CrossRef]

18. Gardner, L. Stability and design of stainless steel structures—Review and outlook. Thin-Walled Struct. 2019, 141, 208–216. [CrossRef]

19. Lim, K.S.; Azraai, S.N.A.; Noor, N.M.; Yahaya, N. An Overview of Corroded Pipe Repair Techniques Using Composite Materials. Int. J. Mater. Metall. Eng. 2015, 10, 19–25.

20. Reda, A.; Thiedeman, J.; Elgazzar, M.A.; Shahin, M.A.; Sultan, I.A.; McKee, K.K. Design of subsea cables/umbilicals for in-service abrasion—Part 1: Case studies. Ocean Eng. 2021, 234, 108895. [CrossRef]

21. Reda, A.; Elgazzar, M.A.; Thiedeman, J.; McKee, K.K.; Sultan, I.A.; Shahin, M.A. Design of subsea cables/umbilicals for in-service abrasion—Part 2: Mechanisms. Ocean Eng. 2021, 234, 109098. [CrossRef]

22. Reda, A.; Forbes, G.L.; Al-Mahmoud, F.; Howard, I.M.; McKee, K.K.; Sultan, I.A. Compression limit state of HVAC submarine cables. Appl. Ocean Res. 2016, 56, 12–34. [CrossRef]

23. Amaechi, C.V.; Chesterton, C.; Butler, H.O.; Gillett, N.; Wang, C.; Ja’E, I.A.; Reda, A.; Odijie, A.C. Review of Composite Marine Risers for Deep-Water Applications: Design, Transition and Mechanics. J. Compos. Sci. 2022, 6, 96. [CrossRef]

24. Ochoa, O.; Salama, M. Offshore composites: Transition barriers to an enabling technology. Compos. Sci. Technol. 2005, 65, 2588–2596. [CrossRef]

25. Wang, C.; Shankar, K.; Morozov, E.V. Global design and analysis of deep sea FRP composite risers under combined environmental loads. Adv. Compos. Mater. 2015, 26, 79–98. [CrossRef]

26. Wang, C.; Sun, M.; Shankar, K.; Xing, S.; Zhang, L. CFD Simulation of Vortex Induced Vibration for FRP Composite Riser with Different Modeling Methods. Appl. Sci. 2018, 8, 684. [CrossRef]

27. Amaechi, C.V.; Gillett, N.; Odijie, A.C.; Hou, X.; Ye, J. Composite risers for deep waters using a numerical modelling approach. Compos. Struct. 2018, 210, 486–499. [CrossRef]

28. Toh, W.; Bin Tan, L.; Jaiman, R.K.; Tay, T.E.; Tan, V.B.C. A comprehensive study on composite risers: Material solution, local end fitting design and global response. Mar. Struct. 2018, 61, 155–169. [CrossRef]
55. Inaudi, D. Long-gauge strain sensors for underwater and deep-water applications. In Proceedings of the 21st International Conference on Optical Fiber Sensors (OFS21), Ottawa, ON, Canada, 15–19 May 2011; pp. 77535R–77535R-4. [CrossRef]

56. Li, H.N.; Ren, L.; Li, D.S.; Zhou, G.D. Advances of structural health monitoring by fiber Bragg grating sensor. In Proceedings of the 2nd International Conference in Structural Health Monitoring and Intelligent Infrastructure, Shenzhen, China, 16–18 November 2005; Ou, J.P.; Li, H., Duan, Z.D., Eds.; Taylor & Francis Group: London, UK, 2006.

57. Jacques, R.C.; Flores, J.V.; Strohaecker, T.R.; Reguly, A. Acoustic emission testing in wires from the tensile armour of flexible risers under load. Insight—Non-Destructive Test. Cond. Monit. 2009, 51, 504–507, 511. [CrossRef]

58. Enota, H.; Gavoyuere, T.; Garnier, P. Flexible Risers Lifetime Extension: Riser In-Service Monitoring and Advanced Analysis Techniques. In Proceedings of the ASME 2017 36th International Conference on Ocean, Offshore and Arctic Engineering, Trondheim, Norway, 25–30 June 2017; Volume 5A. [CrossRef]

59. Criado, A.; Riezu, M.; Fernandez, A.; Oizm, A. Evaluation of OBR for strain measurements in blade testing. In Proceedings of the European Wind Energy Conference, Marseille, France, 16–19 March 2009.

60. Diaz-Maroto, P.; Lopez, A.F.; Larrañaga, B.; Gordo, J.A.G. Free-edge delamination location and growth monitoring with an embedded distributed fiber optic network. In Proceedings of the 2016 8th European Workshop on Structural Health Monitoring (EWSHM 2016), Spain, Bilbao, 5–8 July 2016. Available online: https://www.ndt.net/events/EWSHM2016/app/content/Paper/316_FernandezDiaz-Maroto.pdf (accessed on 28 June 2022).

61. Alexander, C.; Brooks, C. Development and Evaluation of a Steel-Composite Hybrid Composite Repair System. In Proceedings of the IPC 2012 (Paper No. IPC2012-90573), 9th International Pipeline Conference, Calgary, AB, Canada, 24–28 September 2012; pp. 755–769. [CrossRef]

62. Alexander, C. Advanced Techniques for Establishing Long-Term Performance of Composite Repair Systems. In Proceedings of the IPC 2014 (Paper No. IPC2014-33405), 10th International Pipeline Conference, Calgary, AB, Canada, 29 September–3 October 2014. [CrossRef]

63. Alexander, C.; LaVergne, R.; Turner, A. Use of Fiber Optic Technology in Monitoring Steel Sleeves and Composite Wrap Reinforcements. In Proceedings of the 2018 12th International Pipeline Conference, IPC2018, Calgary, AB, Canada, 24–28 September 2018. Available online: https://www.chrisalexander.com/wp-content/uploads/2020/05/IPC-2018-78037-WS-LR-ADV.pdf (accessed on 28 June 2022).

64. Maheshwari, M.; Wu, L.; Yao, Y.; Upadrashta, D.; Yang, Y.; Wang, X.; Gu, H.; Liu, X. Selection and Characterization of Fiber Optic Sensors for Improved Offshore Structural Health Monitoring. Conference Paper. 2017. Available online: https://www.researchgate.net/profile/Muneesh-Maheshwari/publication/320183366_Selection_and_Characterization_of_Fiber_Optic_Sensors_for_Improved_Offshore_Structural_Health_Monitoring/links/59d35f124585150177f9438d/Selection-and-Characterization-of-Fiber-Optic-Sensors-for-Improved-Offshore-Structural-Health-Monitoring.pdf (accessed on 28 June 2022).

65. Wu, L.; Maheshwari, M.; Yang, Y.; Xiao, W. Selection and characterization of packaged FBG sensors for offshore applications. Sensors 2018, 18, 3963. [CrossRef]

66. Corrignan, H.; Ramos, R.; Smith, R.; Kimminau, S.J.; El Hares, I. New Monitoring Technology for Detection of Flexible Armour Wire Failure. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 4–7 May 2009. [CrossRef]

67. Morikawa, S.; Camerini, C.S.; Braga, A.M.; Llerena, R.A. Real time continuous structural integrity monitoring of flexible risers with optical fiber sensors. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 3–6 May 2010. [CrossRef]

68. Braga, A.M.; Morikawa, S.; Camerini, C.S.; Camerini, M.G.; Ribeiro, A.S.; Simoes, T.B. Vibration Monitoring Technique to Detect Failure in Armour Wires of Flexible Risers. In Proceedings of the OTC Brasil, Rio de Janeiro, Brazil, 4–6 October 2011. [CrossRef]

69. Marinho, M.; Camerini, C.; dos Santos, J.; Pires, G. Surface Monitoring Techniques for a Continuous Flexible Riser Integrity Assessment. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 30 April–3 May 2007. [CrossRef]

70. Pitt, G.; Barnett, J.; Thornton, G. Offshore Monitoring and Control Using Optical Fibers. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 6–9 May 1985. [CrossRef]

71. Worsley, J.; Minto, C.; Hill, D.; Godfrey, A.; Ashdown, J. Fibre Optic Four Mode Leak Detection for Gas, Liquids and Multiphase Products. In Proceedings of the Abu Dhabi International Petroleum Exhibition and Conference, Abu Dhabi, United Arab Emirates, 10–13 November 2014. [CrossRef]

72. Weaver, M.A.; Kragas, T.K.; Burman, J.; Copeland, D.L.; Phillips, B.; Seagraves, R. Installation and Application of Permanent Downhole Optical Pressure Gauges and Distributed Temperature Sensing in Producing Deepwater Wells at Marco Polo. In Proceedings of the SPE Annual Technical Conference and Exhibition, Dallas, TX, USA, 9–12 October 2005. [CrossRef]

73. Rahman, M.; Reed, D.A.; Allan, M.E. The Challenges of Full Field Implementation of Fiber-Optic DTS for Monitoring Injection Profile in Belridge Field, California. In Proceedings of the SPE Digital Energy Conference, The Woodlands, TX, USA, 5–7 March 2013. [CrossRef]

74. Kamal, S.Z. Fiber Optic Sensing: Evolution to Value. In Proceedings of the SPE Intelligent Energy Conference & Exhibition, Utrecht, The Netherlands, 1–3 April 2014. [CrossRef]

75. Lovell, J.R. Reducing Intervention in Subsea Wells with Fiber Optic Technology: Deployments and Results. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 6–9 May 2013. [CrossRef]

76. Thodi, P.; Paulin, M.; Forster, L.; Burke, J.; Lanan, G. Arctic Pipeline Leak Detection using Fiber Optic Cable Distributed Sensing Systems. In Proceedings of the OTC Arctic Technology Conference, Houston, TX, USA, 10–12 February 2014. [CrossRef]
101. Sheehan, J.M.; Grealish, F.W.; Harte, A.M.; Smith, R.J. Characterizing the Wave Environment in the Fatigue Analysis of Flexible Risers. *J. Offshore Mech. Arct. Eng.* 2005, 128, 108–118. [CrossRef]

102. Rakshit, T.; Atluri, S.; Dalton, C. VIV of a Composite Riser at Moderate Reynolds Number Using CFD. *J. Offshore Mech. Arct. Eng.* 2008, 130, 011009. [CrossRef]

103. Ravet, F.; Rochat, E.; Borda, C.; Nikles, M.R. Qualification and Validation of DTS/DSS Technology for Umbilical Monitoring. In Proceedings of the OTC Brasil, Rio de Janeiro, Brazil, 29–31 October 2013. [CrossRef]

104. Gazi, N.H.; Al-Humoud, J.; Kotecha, R.; Al-Sabea, S.; Behera, P.; Attar, I.; Shafiq, M.; Al-Mutairi, F. Use of Distributed Temperature Sensors and Permanent Gauges in Shallow Wells to Monitor Real Time Fluid Movement to the Surface and Within the Well Bore. In Proceedings of the SPE Kuwait Oil and Gas Show and Conference, Mishref, Kuwait, 11–14 October 2015. [CrossRef]

105. Shanafield, M.; Banks, E.W.; Arkwright, J.W.; Hausner, M.B. Fiber-Optic Sensing for Environmental Applications: Where We Have Come From and What Is Possible. *Water Resour. Res.* 2018, 54, 8552–8557. [CrossRef]

106. Echtermeyer, A.; Steuten, B. Thermoplastic Composite Riser Guidance Note. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 6–9 May 2013. [CrossRef]

107. Echtermeyer, A.T.; McGeorge, D.; Grave, J.H.L.; Weitzenböck, J. Bonded patch repairs for metallic structures—A new recommended practice. *J. Reinf. Plast. Compos.* 2013, 33, 579–585. [CrossRef]

108. Hugaas, E.; Vedvik, N.P.; Echtermeyer, A.T. Buckling due to external pressure of a composite tube measured by Rayleigh optical backscatter reflectometry and analyzed by finite elements. *Struct. Control Health Monit.* 2018, 25, e2205. [CrossRef]

109. Echtermeyer, A.T. Integrating Durability in Marine Composite Certification. In *Durability of Composites in a Marine Environment;* Solid Mechanics and Its Applications; Davies, P., Rajapakse, Y., Eds.; Springer: Dordrecht, The Netherlands, 2014; Volume 208. Available online: https://www.tremont.fr/rd_technologiques/content/download/64200/865449/file/9-Echtermeyer.pdf (accessed on 28 June 2022). [CrossRef]

110. Duong, C.N. *Composite Repair: Theory and Design;* Wang, C.H., Ed.; Elsevier: Amsterdam, The Netherlands, 2007.

111. Sykes, D.J. Metallurgical Failures in Oil and Gas Pipelines. In Proceedings of the Asia Offshore Energy Conference, Beijing, China, 12–13 January 2012.

112. Guo, B.; Song, S.; Ghalambor, A.; Lin, T. Chapter 17—An Introduction to Condition-Based Maintenance. In *Offshore Pipelines: Design, Installation, and Maintenance,* 2nd ed.; Gulf Professional Publishing: Oxford, UK, 2014; pp. 257–297. [CrossRef]

113. Singh, R. Chapter One—Need for the Study of Corrosion. In *Corrosion Control for Offshore Structures;* Singh, R., Ed.; Gulf Professional Publishing: Boston, UK, 2014; pp. 3–6.

114. Harrop, I.; Summerscales, J. Acoustic Emission testing of the structural integrity of multicore cable. *Br. J. Non-Destr. Test* 1989, 31, 383–386. [CrossRef]

115. Drummond, G.; Watson, J.; Acarnley, P. Acoustic emission from wire ropes during proof load and fatigue testing. *NDT E Int.* 2007, 40, 94–101. [CrossRef]

116. Casey, N.; Holford, K.; Taylor, J. The acoustic evaluation of wire ropes immersed in water. *NDT Int.* 1987, 20, 173–176. [CrossRef]

117. Casey, N.; Laura, P. A review of the acoustic-emission monitoring of wire rope. *Ocean Eng.* 1997, 24, 935–947. [CrossRef]

118. Hanzawa, M.; Yokota, H.; Toda, Y.; Yokoyama, K. Fatigue Behavior of Large-Diameter Wire Ropes. *Soc. Pet. Eng. J.* 1982, 22, 420–428. [CrossRef]

119. Bogarin, J.A.G.; Echtermeyer, N.F.F. Integration of knowledge sources for flexible pipe evaluation and design. *Expert Syst. Appl.* 1996, 10, 29–36. [CrossRef]

120. Carneval, R.O.; Marinho, M.G.; dos Santos, J.M. Flexible line inspection. In Proceedings of the 9th European Non-Destructive Testing Conference, Berlin, Germany, 25–29 September 2006; Volume 106, p. 1.

121. Chen, J.; Huang, Y.; Dong, X. Study on the splash zone corrosion protection of carbon steel by sacrificial anode. *Water Resour. Res.* 2018, 54, 8552–8557. [CrossRef]

122. Lyons, G.; Witz, J.; Brown, D. Measurements from the Emerald instrumented flexible riser. In *DNV Offshore Standard DNV-OS-C501; Structural Design of Offshore Units—WSD Method;* Det Norske Veritas (DNV): Oslo, Norway, 2017. Available online: https://rules.dnv.com/docs/pdf/DNV/OS/2017-07/DNV-OS-C501.pdf (accessed on 28 June 2022).

123. Shanafield, M.; Banks, E.W.; Arkwright, J.W.; Hausner, M.B. Fiber-Optic Sensing for Environmental Applications: Where We Have Come From and What Is Possible. *Water Resour. Res.* 2018, 54, 8552–8557. [CrossRef]

124. Picksley, J.; Kavanagh, K.; Garnham, S.; Turner, D. Managing the Integrity of Flexible Pipe Field Systems: Industry Guidelines. In *Composite Repair: Theory and Design;* Wang, C.H., Ed.; Elsevier: Amsterdam, The Netherlands, 2007.

125. Echtermeyer, A.T. Integrating Durability in Marine Composite Certification. In *Durability of Composites in a Marine Environment;* Solid Mechanics and Its Applications; Davies, P., Rajapakse, Y., Eds.; Springer: Dordrecht, The Netherlands, 2014; Volume 208. Available online: https://www.tremont.fr/rd_technologiques/content/download/64200/865449/file/9-Echtermeyer.pdf (accessed on 28 June 2022). [CrossRef]

126. DNVGL, Offshore Standards DNVGL-OS-C201; Structural Design of Offshore Units—WSD Method; Det Norske Veritas (DNV): Oslo, Norway, 2017. Available online: https://rules.dnv.com/docs/pdf/DNV/OS/2017-07/DNV-OS-C201.pdf (accessed on 28 June 2022).

127. DNV, Recommended Practice DNVGL-RP-C301; Design, Fabrication, Operation and Qualification of Bonded Repair of Steel Structures. Det Norske Veritas (DNV): Oslo, Norway, 2015. Available online: https://rules.dnv.com/docs/pdf/DNV/RP/2015-07/DNVGL-RP-C301.pdf (accessed on 28 June 2022). [CrossRef]

128. DNV, Offshore Standard DNV-OS-C501; Composite Components. Det Norske Veritas (DNV): Oslo, Norway, 2013. Available online: https://rules.dnv.com/docs/pdf/dnvpm/codes/docs/2013-11/OS-C501.pdf (accessed on 4 March 2022).
158. Baldwin, D.; Lo, K.; Long, J. Design Verification of a Composite Production Riser. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 4–7 May 1998; pp. 103–112. [CrossRef]

159. Salama, M.M.; Murali, J.; Baldwin, D.D.; Jahnson, O.; Meland, T. Design Consideration for Composite Drilling Riser. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 3–6 May 1999; pp. 1–11. [CrossRef]

160. Salama, M. Lightweight Materials For Deepwater Offshore Structures. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 5–8 May 1986; pp. 297–304. [CrossRef]

161. Sparks, C.; Odrzu P.; Bono, H.; Metivaud, G. Mechanical Testing of High-Performance Composite Tubes For TLP Production Risers. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 2–5 May 1988; pp. 467–472. [CrossRef]

162. Tamarelle, P.; Sparks, C. High-Performance Composite Tubes for Offshore Applications. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 27–30 April 1987; pp. 255–260. [CrossRef]

163. Picard, D.; Hudson, W.; Bouquier, L.; Dupupet, G.; Zivanovic, I. Composite Carbon Thermo-plastic Tubes for Deepwater Applications. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 30 April–3 May 2007; pp. 1–9.

164. Kim, W.K. Composite Production Riser Assessment. Ph.D. Thesis, Department of Mechanical Engineering, Texas A & M University, College Station, TX, USA, 2007. Available online: https://core.ac.uk/download/pdf/4272879.pdf (accessed on 18 March 2022).

165. Wang, C.; Shankar, K.; Morozov, E.V. Design of deep sea composite risers under combined environmental loads. In Proceedings of the 9th Composites Australia & CRC-ACS Conference Diversity in Composites Conference, Lutra Australia, 15–16 March 2012; pp. 1–14.

166. Wang, C.; Shankar, K.; Morozov, E.V. Local design of composite risers under burst, tension and collapse cases. In Proceedings of the 18th International Conference on Composite Materials (ICCM18), Jeju, Korea, 22 August 2011; pp. 1–6. Available online: http://www.iccm-central.org/Proceedings/ICCM18/proceedings/data/2%20Oral%20Presentation/Aug22%20Monday%20/50%20%20Applications%20of%20Composites/M4-1-1P0161.pdf (accessed on 4 March 2022).

167. Wang, C.G.; Shankar, K.; Ashraf, M.; Morozov, E.V.; Ray, T. Surrogate-assisted optimisation design of composite riser. Proc. Inst. Mech. Eng. Part L J. Mater. Des. Appl. 2016, 230, 18–34. [CrossRef]

168. Wang, C.; Shankar, K.; Morozov, E.V. Tailored design of top-tensioned composite risers for deep-water applications using three different approaches. Adv. Mech. Eng. 2017, 9. [CrossRef]

169. Singh, M.; Ahmad, S. Bursting Capacity and Debonding of Ultra Deep Composite Production Riser: A Safety Assessment. In Proceedings of the ASME 2014 35rd International Conference on Ocean, Offshore and Arctic Engineering, San Francisco, CA, USA, 8–13 June 2014; Volume 6A. [CrossRef]

170. Singh, M.; Ahmad, S. Probabilistic Analysis and Risk Assessment of Deep Water Composite Production Riser against Fatigue Limit State. In Proceedings of the ASME 2015 34th International Conference on Ocean, Offshore and Arctic Engineering, Safety and Reliability, St. John’s, NL, Canada, 31 May–5 June 2015; Structures, Safety and Reliability. Volume 3. [CrossRef]

171. Ragheb, H.; Goodridge, M.; Pham, D.; Sobey, A. Extreme response based reliability analysis of composite risers for applications in deepwater. Mar. Struct. 2021, 78, 103015. [CrossRef]

172. Ragheb, H.; Sobey, A. Effects of extensible modelling on composite riser mechanical responses. Ocean Eng. 2021, 220, 108426. [CrossRef]

173. Carpenter, C. Qualification of Composite Pipe. J. Pet. Technol. 2016, 68, 56–58. [CrossRef]

174. Huang, Z.; Zhang, W.; Qian, X.; Su, Z.; Pham, D.C.; Sridhar, N. Fatigue behaviour and life prediction of filament wound CFRP pipes based on coupon tests. Mar. Struct. 2020, 72, 102756. [CrossRef]

175. Huang, Z.; Qian, X.; Su, Z.; Pham, D.C.; Sridhar, N. Experimental investigation and damage simulation of large-scaled filament wound composite pipes. Compos. Part B Eng. 2019, 184, 107639. [CrossRef]

176. Schuett, C.; Paternoster, A. Full Generic Qualification of Nylon 12 Carbon Fiber Composite for Dynamic Thermoplastic Composite Pipe and Hybrid Flexible Pipe Applications. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 16–19 August 2021. [CrossRef]

177. Cederberg, C.A.; Baldwin, D.D.; Bhalla, K.; Tognarelli, M.A. Composite-Reinforced Steel Drilling Riser for Ultra-deepwater High Pressure Wells. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 6–9 May 2013. [CrossRef]

178. Andersen, W.; Anderson, J.; Landraault, L. Full-Scale Testing of Prototype Composite Drilling Riser Joints-Interim Report. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 4–7 May 1998; pp. 147–154. [CrossRef]

179. Black, S. Offshore Applications: The Future Is Now. Composites World, Issue: 4/1/2003. Available online: https://www.compositesworld.com/articles/offshore-applications-the-future-is-now (accessed on 28 June 2022).

180. USCG PFM 1-98 Policy File Memorandum on the Fire Performance Requirements for Plastic Pipe per IMO Resolution, A.753(18); USCG: Washington, DC, USA, 1998.

181. USCG PFM 2-98 Policy File Memorandum on the Fire Performance Requirements for Plastic Pipe per IMO Resolution A.753(18); USCG: Washington, DC, USA, 1998.

182. Mishra, M. Encyclopedia of Polymer Applications; CRC Press: Boca Raton, FL, USA, 2018.

183. Wan, B. Using fiber-reinforced polymer (FRP) composites in bridge construction and monitoring their performance: An overview. In Advanced Composites in Bridge Construction and Repair; Woodhead Publishing: Cambridge, UK, 2014; pp. 3–29.
185. Ma, W.F.; Luo, J.H.; Cai, K. Discussion about Application of Composite Repair Technique in Pipeline Engineering. *Adv. Mater. Res.* 2011, 311–313, 185–188. [CrossRef]

186. Martins, C.O.D.; Reguly, A. Micromagnetic stress evaluation of flexible riser tensile armours. *Insight* 2009, 51, 8–20. [CrossRef]

187. Almeida, R.M.; Rebello, J.M.A.; Vaz, M.A. Reliable radiographic inspection of flexible risers for the oil industry. *AIP Conf. Proc.* 2010, 1211, 1689–1696. [CrossRef]

188. Macfarlane, C. Flexible riser pipes: Problems and unknowns. *Eng. Struct.* 1989, 11, 281–289. [CrossRef]

189. Alexander, C.R. Development of Composite Repair System for Reinforcing Offshore Risers. Ph.D. Thesis, Department of Mechanical Engineering, Texas A&M University, College Station, TX, USA, 2007. Available online: http://oaktrust.library.tamu.edu/bitstream/handle/1969.1/ETD-TAMU-2534/ALEXANDER-DISSERTATION.pdf?sequence=1 (accessed on 15 February 2022).

190. Chan, P.H. Design Study of Composite Repair System for Offshore Riser Applications. Ph.D. Thesis, Department of Mechanical, Materials and Manufacturing Engineering, The University of Nottingham, Malaysian Campus, Semenyih, Malaysia, 2015. Available online: http://eprints.nottingham.ac.uk/33455/1/CHAN%20PARK%20HINN%20%20Design%20Study%20of%20Composite%20Repair%20System%20for%20Offshore%20Riser%20Applications.pdf (accessed on 15 February 2022).

191. Alexander, C.; Ochoa, O. Extending onshore pipeline repair to offshore steel risers with carbon-fiber reinforced composites. *Compos. Struct.* 2010, 92, 499–507. [CrossRef]