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Review on the design and mechanics of bonded marine hoses for Catenary Anchor Leg Mooring (CALM) buoys

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Abstract

In recent times, there is a rise in the application of bonded marine hoses on floating offshore structures (FOS). These increased developments on bonded marine hoses have led to their deployment on CALM, SALM, and other conventional offshore buoy systems. Classification of bonded marine hoses includes floating hoses, submarine hoses, and reeling hoses. The mechanics of hose motion is relative to different operations, such as twists, turns, torques, reeling, pipe-laying, etc. However, despite having multi-layers, the hose response is susceptible to high hose curvatures, kinking, and crushing loads. This paper presents a comprehensive review on the design and mechanics of bonded marine hoses for CALM buoys. The study also explores fluid transfer via these bonded flexible risers (or marine hoses). Governing mathematical formulations on bonded marine hoses attached to CALM buoy systems were presented. This paper presents a review of theoretical, numerical, and experimental investigations on hoses. Discussions were made on recent developments, structural connections, industrial operations, field applications, and dynamic responses, concluding on the merits of marine hoses.

Keywords:

Bonded Marine Hose; Bonded Flexible Composite Risers; Mechanics; Catenary Anchor Leg Mooring (CALM) buoy: Oil and Gas Platform; Floating and Submarine Hoses

Abbreviation List:

3D – Three Dimensional
ABS – American Bureau of Shipping
ADCP -Acoustic Doppler Current Profiler
API – American Petroleum Institution
BSI - British Standards Institution
CAE - computer-aided engineering
CALM - Catenary Anchor Leg Mooring
CAPEX -Capital Expenditure
CBM - Conventional buoy mooring
CFD Computational Fluid Dynamics
CFRP - Carbon Fibre Reinforced Polymer
CL - Chinese-lantern (hose configuration)
CoG – Centre of Gravity
DC - Double Carcass
DNVGL - Det Norkse Veritas & Germanischer Lloyd
DOE - Design Of Experiment
DP - Dynamic Position
EN- Europäische Norm ("European Norm") Standards
FAT - factory acceptance test
FE- Finite Element
FEA- Finite Element Analysis
FEM- Finite Element Modelling
FOS - Floating Offshore Structure
FPSO – Floating, Production, Storage and Offloading
FRP - Fibre Reinforced Polymer
FSO - Floating storage and offloading
FSP - Floating storage and processing
FTM - Fixed tower mooring systems
GMPHOM – Guide to Manufacturing and Purchasing Hoses for Offshore Moorings
GoM – Gulf of Mexico
Hechanics – Hose Mechanics
HEV - Hose End Valve
Hose1, Hose2 – Leeside1, Weatherside2 of Hose-String
HPHT - High Pressure -High Temperature
IMO – International Maritime Organisation
IMS - Integrated Monitoring Systems
ISO- International Standards Organisation
LNG - Liquified Natural Gas
LPG - Liquid Petroleum Gas
MBR - Minimum Bending Radius
MCI - Metal Composite Interface
NIS - Nigerian Industrial Standards
OCIMF - Oil Companies International Marine Forum
PLEM - Pipeline End Manifold
PLUTO - PipeLine Across The Ocean
RHS - Right Hand Side
SALM - Single Anchor Leg Mooring
S.F - Safety Factor
SC - Single Carcass
SCR - Steel Catenary Risers
SLF - Stress Loading Factors
SPM - Single Point Mooring
SPM - Single Point Mooring
STD - Standard Type
SURP - Subsea Umbilical Risers And Pipelines

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SWIR - Sea-Water Intake Riser
TDS - Touch Down Sites
UF - Utlilization Factors
UK - United Kingdom
UM - Utilization Matrix
UTS - Universal Transfer System
VIV - Vortex-Induced Vibration
WA - Weight-Added
WWII - World War II

1.0 Introduction

Over the past few decades, offshore engineering has relatively advanced in both knowledge base and technology. First and foremost, the increasing global energy demand has been the main driver within the offshore sector. More than 60% of energy consumption within the United States, for instance, is based on oil and gas products achieved by the offshore industry (CSS 2020, EIA 2017, IEA 2017). With the need to transport these fluid from seabeds and oil wells offshore, it is pertinent to have conduits such as composite marine risers (Amaechi C.V 2021, Amaechi C.V et al. 2017, 2019a, 2019b, 2021a, 2021b, 2021c; Pham D.C. et al. 2016), reinforced thermoplastic pipes (Kuang Yu et al. 2015, 2017) and offshore/marine hoses (Yokohama 2016; EMSTEC 2016; Amaechi C.V. et al. 2019c, 2019d, 2021d, 2021e, 2021f). Different activities within the oil and gas industry mostly require these marine hoses and SURP (subsea umbilicals, risers, and pipelines) devices. These activities include loading, offloading, exploration, and extraction of oil and gas, offshore mining, gas liquefaction, seawater intake, and sea minerals transportation. As such, there is the need for the application of steel catenary risers (SCR), composite marine risers, unbonded flexible risers cum bonded flexible risers (also called bonded marine hoses). Due to the slender-flexible nature of these tubular structures, fluid transfer techniques have improved. In offshore fields, submarine pipelines, marine hoses and marine risers are usually the commonly used conduits. They are utilised in water injection, product transfer, and fluid transport. These structures have to be manufactured to withstand high pressure -high temperature (HPHT) environments. These HPHT marine hoses are deployed on different mooring terminals for un(loading) operations (Bai Y. & Bai Q., 2005, 2010). A typical CALM Buoy hose system with its components using the Chinese-Lantern (CL) Configuration is represented in Figure 1.

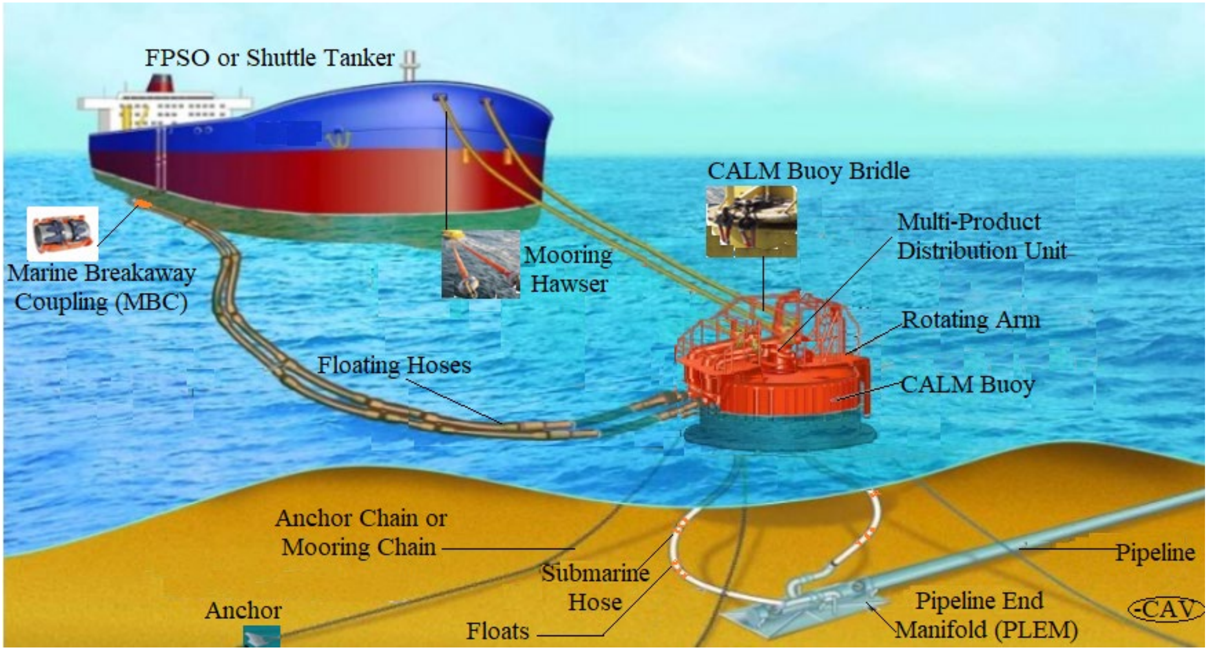

Figure 1 Offloading system via marine hoses showing CALM Buoy in Chinese-Lantern (CL) Configuration.

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In recent times, there are improvements in the manufacturing processes for these HPHT tubular marine. Application of these structures also has increased utilisation on different moored marine platforms and floating offshore structures (FOS). These structures include Catenary Anchor Leg Mooring (CALM) buoys, Single Anchor Leg Mooring (SALM) buoys, and other conventional offshore buoy systems. These are usually attached to bonded marine hoses, ranging from floating, submarine, reeling, catenary to sea-water intake riser (SWIR) hoses (Yokohama 2016; Technip 2006; ContiTech 2017, 2019, 2020; EMSTEC 2016). Since hose utilisation has been increasingly popular in recent years, it is necessary to review the hose mechanics (or hechanics), design configurations, and developments. A particular niche for marine hoses is the short-term production in shallow water and other loading/unloading applications. Different environmental conditions require specific needs, connections, and mooring configurations. Generally, these mooring systems include SALM, CALM, and tandem mooring (OIL 2014, 2015; Trelleborg 2016, 2017; SBMO 2012). There are other conventional mooring designs and deepwater export line configurations deployed on marine hoses. Figure 2 is an illustration of some design arrangements for marine hoses and marine risers. Concerning the marine hoses, their application has been increasingly used to link CALM buoys to the transporting FPSOs (Wang 2015; Eriksson et al. 2006; Berteaux et al. 1977, Amaechi C.V. et al. 2019b). The hose is also attached to the pipeline end module (PLEM) to enable the transfer of oil products to shuttle tankers from offshore platforms. CALM buoy hose configurations include Lazy-S, Steep-S, Chinese-lantern (CL), and weight-added (WA) configurations (Stearns 1975; Nooij 2006, Amaechi C.V. et al. 2021g, 2019c). As shown in Figure 1, the CALM buoy hose system is connected to a shuttle tanker with floating and submarine hoses. Usually, a standard hose-string is made up of an assembly for the hose-housing having rubberised layers, reinforced fibres and end-fittings of steel (HoseCo 2017; OCIMF 2009; Bluewater 2009b, 2011). In principle, the hose-housing assemblies have to be well reinforced to withstand different environmental conditions. Thus, improvements in recent marine hoses, such as Trelleborg's dual carcass hoses and the inclusion of composite materials in the assembly of offshore hoses (Trelleborg 2016, Zhou et al. 2018, Tonatto et al. 2018). There is a gap on the control of marine hoses, however recent studies exist on the control of flexible risers (Hu X. et al. 2021, Zhao Z. et al. 2019, 2021a, 2021b). Another issue of hose application is crushing load effect on hoseline reeling. Installing subsea pipelines with diameter of about 20 inches using reeling is a rapid, dependable, and cost-saving technique, as shown in Figure 3. In a nutshell, Despite the availability of newly developed structural designs, advances and design recommendations, the challenges related to flexible bonded marine hoses on single point mooring (SPM) terminals have not been extensively studied. Thus, the need for this comprehensive review emphasising theoretical, numerical, and experimental investigations of the marine hoses.

In this paper, the review on the mechanics and design of bonded flexible risers (or bonded marine hoses) and offshore offloading hose systems has been carried out. A comprehensive review of hose development, hose structures, industry application, recent developments, design criteria, mechanicals behaviour, and hose failures has been presented. Section 1 presents the introduction, Section 2 presents aspects of background and development, Section 3 presents design criteria, testing and analysis of marine hoses, Section 4 presents mechanical behaviour model of marine hoses, while Section 5 gives the conclusion with application benefits (or merits) of marine hoses. This review is necessary for hose manufacturers, SPM designers, and industry standards. The recommendations on this review were drawn based on recent developments and presented according to current industry standards like OCIMF, IMO, NIS, BSI, EN, ABS, API, DNVGL and ISO standards.

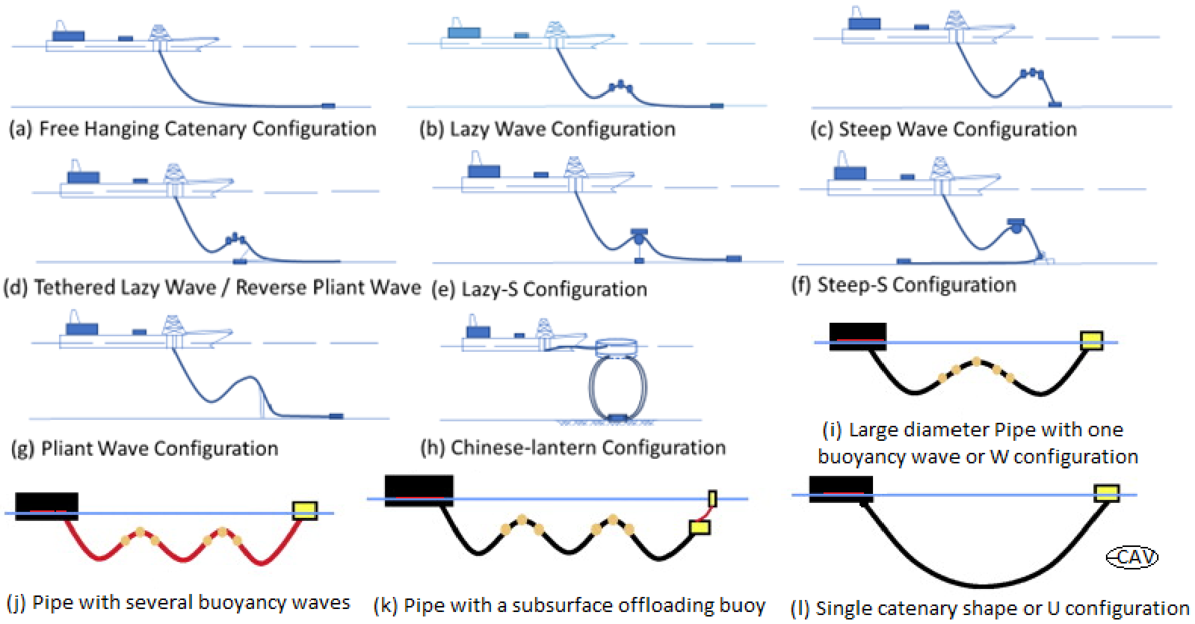

Figure 2 State-of-the-art configurations for marine hoses and marine risers

2.0 Background on Bonded Marine Hoses

In this section, the background on hose development, purchase requirements, and fluid transfer are presented.

2.1 Historical Timeline on Marine Hoses

For offshore oil and gas production, flexible marine hoses, flexible risers, and pipeline technology are still being developed. Flexible pipes, on the other hand, have a wide range of applications in other industries before being brought to the renewable-offshore industry. Flexible pipelines were formerly assumed to be low-maintenance and didn't require routine inspection. Recent studies on hose failures, riser failures, and flexible pipe failures, on the other hand, have revealed that some documented occurrences of these installations and assets have occurred offshore. As a result, there is a pressing need to improve design, manufacturing, service delivery procedures, and production grades. Hoses, pipes, end-terminations, and accessories are all in need of improvement. Recent studies, on the other hand, demonstrate that tremendous progress has been made since their inception. The historical timeline is detailed in literature (Yokohama 2016, Amaechi et al. 2021b, 2021c, 2021c, Sparks C. 2018). The PLUTO (PipeLine Across The Ocean) project, which delivered petroleum from the United Kingdom (UK) to Normandy, France, under the English Channel during World War II (WWII), was the first to introduce and implement the concept of a flexible armoured maritime pipeline on a significant scale. The design incorporated high-voltage maritime power line technology. The historical timeline on progress made in the development of bonded hoses shows new innovations over the years by different hose manufacturers, such as Yokohama, as shown in Figure 3. There are a number of projects that use marine hoses by various hose manufacturers, presented in Appendix A, Table 11. It shows forty (40) current offloading hose systems, CALM buoys, and industry operators.

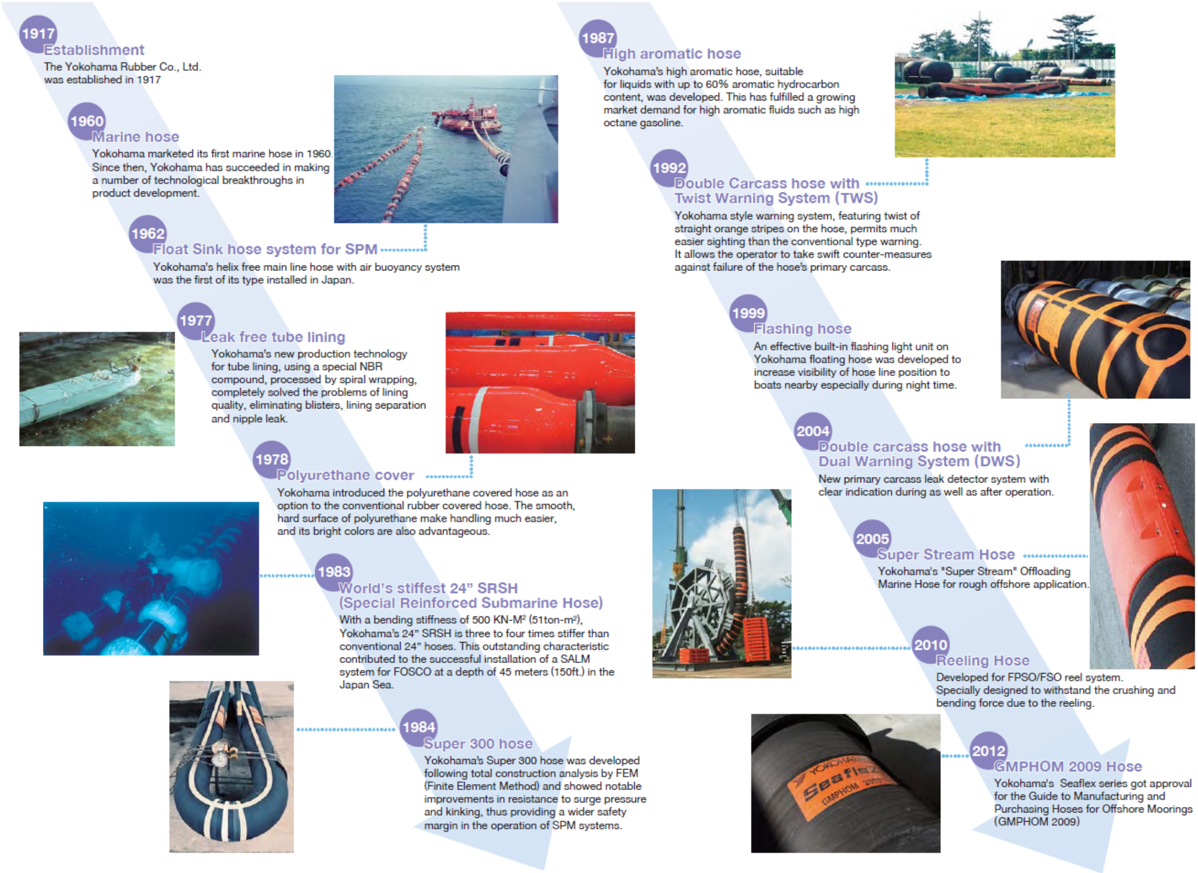

Figure 3 Historical timeline of bonded marine hoses by Yokohama- hose manufacturer (Reproduced, Courtesy: Yokohama)

2.2 Product Development on Marine Hoses

Product development is a key stage in manufacturing bonded marine hoses. The development of bonded marine hoses are based on different design techniques, design loads, and marine hose models. Early designs were reported over six (6) decades ago in literature as patent publications. A documented foremost-related patent was on a robust drilling riser of fibre reinforced polymer (FRP) composite material with glass fibre and coat-painted using epoxy (Ahlstone 1973, Salama and Spencer, 2010, Sparks 2018). Details on the patent development on marine hoses and related SURP components are presented in Section 2.3. However, marine structures are designed based on the design requirements, operating conditions, design loadings, test development/qualification, mechanical behaviour, and structural design. The design requirement of different hose-riser-pipe systems is summarised in Table 1. These cover marine risers (production risers and drilling risers), hoses (floating, submarine, catenary and reeling) and generic tubular pipes (umbilicals, flow-lines, jumpers, choke and kill lines).

However, marine hoses are susceptible to different failure issues (Li X., et al. 2018, Patel and Seyed 1995, Chakrabarti and Frampton 1982, Zhou et al. 2018). The hose failures can be due to kinking, excessive burst pressure, wrong operational use (such as transfer of fluid that it was not designed for), corrosion damage from end-fitting or nipple, and failure due to induced bending moments cum internal pressure loadings. As such, it is important to have working offshore loading and discharging systems that has large flexibility, high feasibility and efficient operational utility. Thus, the importance of the application of multi-layered offshore hoses with capacity to withstand various challenges, including high pressure, high moments, heavy load impacts and harsh environment. To this end, the main load-bearing components of the marine hose layer, that is, the end fitting (Toh

W. et al. 2018, Pham D.C. et al. 2016, Chen Y. et al. 2016, Lassen T. et al. 2014), the core reinforcement normally a steel helical wire (Cao Q. 2018, Van Den Horn & Kuipers, 1988, Kuipers & van der Veen, 1989, Molnár et al. 1990, Bregman et al. 1993) or tensile carcass (Gautam M. et al. 2016, Drumond G.P., et al. 2018, Løtveit S.A. 2009, 2018) and the reinforcement layers (Amaechi C.V. et al. 2019a, Zhou Y. et al. 2018) are very important. However, there is a limitation on the vortex-induced vibration (VIV) studies on bonded flexible risers (such as bonded marine hoses), unlike the VIV of other marine risers (such as SCRs and unbonded flexible risers) which have been extensively researched (Wu X. et al 2012, Hong et al. 2018).

Other hose products are Trelleborg's Reeline and dual carcass hoses, which have a unique offering in the hose market (Trelleborg 2020, 2019, 2018, 2016a, 2016b, 2012). According to Lagarrigue V. et al. (2018), Trelleborg cryogenic hoses can produce turnkey solutions that dramatically lower the CAPEX (capital expenditure) and environmental effect of liquified natural gas (LNG) import infrastructure. They also enable ship-to-shore and ship-to-ship transfers in new places, even in adverse weather. In October 2017, this technology was put to the test in the first sea launch of the Universal Transfer System (UTS), which was developed in collaboration with Connect LNG and Gas Natural Fenosa. This launch's success highlighted the enormous potential of floating cryogenic pipes in terms of unleashing new infrastructural options. To reduce boil-off and assure safety, Trelleborg's dual carcass hoses were designed by incorporating integrated monitoring systems (IMS). Another aspect of hose-riser development is the control systems which has had high traction in recent times. Adaptive robust control of flexible riser systems have been modelled separately (Zhao et al. 2021a, 2021b, 2019a, 2019b, 2017), and coupled models with vessel dynamics (He et al. 2021, 2015a, 2015b, Ge et al. 2010) and during hose-riser installation (He et al. 2014, 2013, 2011, Nguyen et al. 2013, Do 2017a, 2017b). These control systems have been incorporated in marine hoses risers. For the hose's buoyancy floats used in export hoses and other marine hose configurations, an adjustable buoyancy system was devised by Trelleborg (Lai, L. S. H. 2018, Gaskill C. et al. 2018). The hose manufacturer's commitment to innovation in oil transfer systems is demonstrated by Reeline hoses. Reeline hoses are reeling hoses, which also provide optimal operability, lifetime, and safety. These hoses are made with Trelleborg's nippleless hose technology, which results in a flexible bonded oil hose that is specifically suited for reeling operations, making installation easier, lowering opex, and freeing up valuable deck space for offshore operations. They feature Trelleborg's dual-carcass structure, which ensures safety and long service life even in the most extreme environments.

Table 1 Hose-riser-pipe related system design requirement, adapted from API 17K

General Requirement	Hose Requirement (Loading & Discharge)	Riser Requirement	Flowline Requirement
Connection systems Corrosion protection Exothermal chemical reaction cleaning Fire requirement Gas absorption and RGD (rapid gas decompression) Gas venting Inspection and condition monitoring Installation requirements Interface definitions Pigging and TFL requirements Piggyback lines Thermal insulation	Connection systems Design load cases Hose Configuration Hose installation Guides and supports Mooring line design Operational procedures Pipe attachments Vessel data	Connection systems Design load cases Interference requirements Pipe attachments Riser Configuration Vessel data	Crossover requirements Design load cases Routing of flowlines Supports and guides Pipe attachments Upheaval buckling On-bottom stability Criteria for Protection

2.3 Patent Development on Marine Hoses

Different design patents on the advances made in marine hoses exist in patent publications. Figure 4 shows a ship-to-ship hose system, having different hose components and hose types. These hoses were invented under various hose patents (Horvath et al. 1970, 1977; Witz J. A. et al., 2011, 2013). However, these advances stem from other systems like composite marine riser pipes (Amaechi 2021; Amaechi et al. 2019a, 2019b, 2021a, 2021b, 2021c), and marine riser deployed on semisubmersibles (Amaechi et al. 2021m, 2021n, 2021o, 2021p). Over the years, there has been significant growth in developing reinforced hoses (Terashima et al. 1996, Nakane 1935, Istvan G. et al. 2005), hose connections (Andrick et al. 1997, Maclachlan 1940, Muller 1941, 1949) and hose couplings (Castelbaum et al. 1984, Eisenzimmer 1982, Feiler et al. 1999, 1950, Goddard 1998, Goodall 1940). In same vein, there has also been developments achieved in other SURP components like composite marine riser (Pierce 1989, Gallagher 1995, Humphreys 2006), rigid FRP pipes (Pierce 1989, Starita 2005, Humphreys 2006), the end connections (Policelli 1989, 1993, Simmons 1993, Friedrich et al. 1998, Anderson et al. 1998, Baldwin et al. 2000), and bonded flexible risers (Ambrose 1979, Asano et al. 1986, Secher et al. 2000, Winzen et al. 1999).

Other advances based on offshore hose connection systems have also been reported in filed patents. Schirtzinger (1969) patented an apparatus for loading and offloading vessels. Morgan and Lilly (1974) patented a transfer system for suboceanic oil production. Joubert et al. (1981) patented a device that uses a flexible pipe to move fluid across a liquid body. Remery (1981) patented a device for transporting a material from a designated location on a bottom beneath the sea surface to the body of a buoy. In recent times, Brown and Poldervaart (1996) patented an offshore fluid transfer mechanism for a moored floating unit. Antal et al. (2001) patented a construction on high-pressure flexible hose and the manufacturing process. Isnard et al. 1999 patented a vessel with a disconnectable riser supporting buoy. Other related developments include CALM buoys (Braud et al. 1998, Nandakumar et al. 2002, Busch 1987), mooring systems (Hampton 1991, De Baan 1991, Urdshals et al. 1994, Flory 1976, Coppens and Poldervaart, 1984) and marine risers (Mungall et al. 1997, Olufsen et al. 1997, Panicker et al. 1984). These technologies all stem from the earlier developments on flexible pipes and flexible risers transfer systems (Shotbolt 1988, Yamada 1987, Blanchard and Anastasio 2016). Several (un)loading components can be seen on Figure 4.

Some of these (un)loading hoses and flexible pipese are made of composite materials. The selection of fibre reinforcements and materials for the cover or liner differs among these patented designs of rigid composite pipes and flexible hoses. Flexible composite risers and flexible offshore hoses have also gotten a lot of interest since they are less expensive and take less time to instal than rigid riser pipes for marine systems. Goldsworthy and Hardesty (1973) proposed a technique and device on fabricating FRP pipes that were filament wound with continuous length in the early 1970s. Carter (1985) described a machine that may be used to make continuously created longitudinally reinforcing plastic pipes. Two separate designs on end-connection plus FRP spoolable pipes for it were patented by SasJaworsky and Williams (1994, 1999). Quigley et al. (2000) invented a composite spoolable tube with an outside protective layer, a pressure barrier, fibre composite layers, interface layer and an inner liner. Song and Estep (2006) created a spoolable composite coiled tubing connector with two housing types that could be put together to connect the coiled tubes. These advances led to the hose-riser configurations in Figures 1-4. However, different hose problems have been solved from these developed hoses concepts, which led to advances in single point moorings (Sao et al. 1987; Wichers 2013; Obokata 1987; Obokata & Nakajima 1988) and various forms of offloading hose systems (Cao Q. et al. 2017, 2018; Amaechi et al. 2019a, 2019b, 2021g, 2021h). These were achieved by different studies, such as scaled models (Ricbourg et al. 2006; Cunff et al. 2007; Ryu et al. 2006; O'Donoghue & Halliwell 1990; Quash & Burgess 1979; Pinkster & Remery 1975), experiment on test rigs (Tschoepe & Wolfe 1981; Young et al. 1980), field measurements (Brady et al. 1974; Saito et al. 1980; Lebon & Remery 2002), mathematical modelling (Brown & Elliott 1988; Zhang et al. 2015; Bree et al. 1989; Huang & Leonard 1989; Brown 1985a; Brown 1985b; Donoghue & Halliwell 1990) and numerical simulations (Duggal & Ryu 2005; Roveri et al. 2002; Amaechi et al. 2021i, 2021j, 2021k, 2021l). In subsequent sections, more discussion on marine hoses will be conducted.

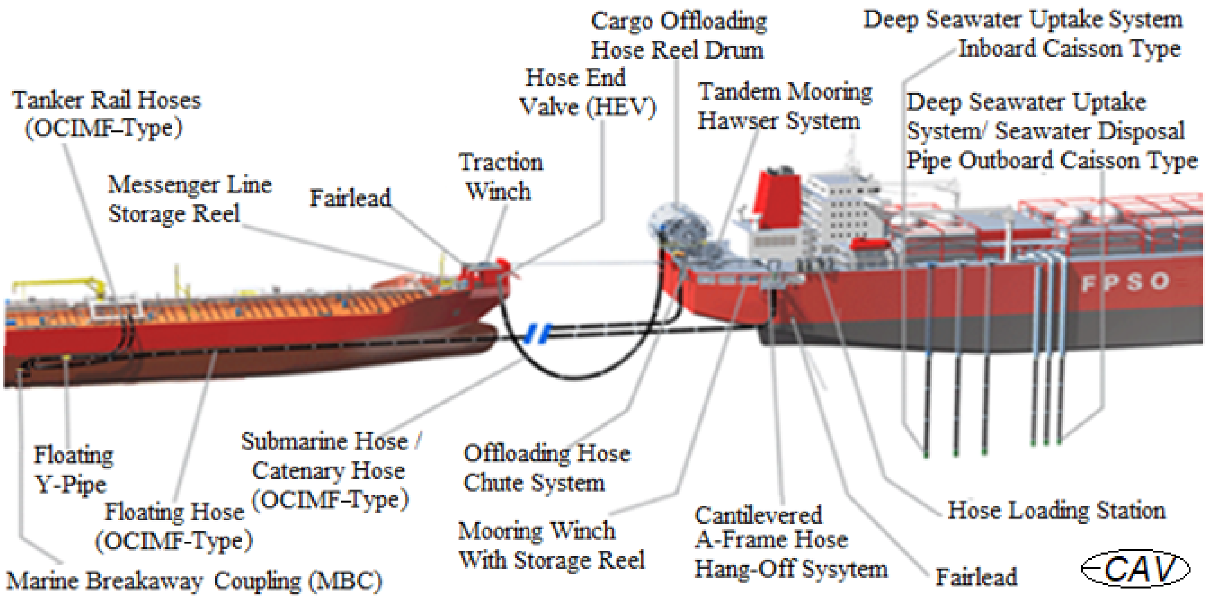

Figure 4 Offshore ship-to-ship transfer using loading & offloading marine hoses, showing various OCIMF-type hoses (Adapted, Courtesy: Offspring International).

2.4 Loading conditions of Marine hoses

The mechanical behaviour of marine hoses is dependent on the loading conditions. Pavlou (2013) identified the loads acting on offshore pipes, riser and hoses and classified them into two main categories: installation phase and operational phase, as presented in Table 2. Like other marine riser systems, marine hoses respond to the motion of the floating offshore structure (FOS) asnd other loadings (Odijie et al. 2017, Amaechi et al. 2021m, 2021n, 2021o, 2021p). The loads are static during the installation stage, but both static and dynamic loading situations can exist during the operational stage. Regarding the mechanical performance of bonded marine hoses, it has to pass some tests as identified in GMPHOM OCIMF (2009) specification. Figure 5 shows the typical duration for OCIMF recommended hydrostatic pressure test of bonded marine hoses. Another issue that occurs during loading tests of bonded marine hoses is the body of the hoses may rupture under burst tests. Figure 6 shows typical experimental load tests on hoses for (a) bending, (b) hydrostatic pressure, (c) torsion and (d) burst. Based on failure due to dynamic loadings, damage analysis, particularly on hose fatigue, is recommended to guarantee that the sustainability and safety of the marine hose or riser system is ensured. This is used in calculating the marine hose' design life. Other issues that can affect the loading include deformation and possible rupture due to creep and should be taken into account in loading history having long-term cases (Yu K. et al., 2017, 2015). Based on the design of offshore hoses and flexible risers as identified in Table 1, there are different material fatigue and creep theories based on damage mechanics. These can be used as benchmarking hose designs, thus effective design tools with different levels of checks. Since operational loads are usually less critical than installation loads for offshore pipelines (Pavlou, 2003), it is also important to do critical checks. Installation loads are a function of the installation method used as identified on Table 2.

Table 2 Classification of loads acting on composite pipes, flexible risers and offshore hoses

Classification of loads	**Loading types**	**Checks**			
		Buckling	**Creep**	**Fatigue**	**Failure Criteria**
Installation Loads	Bending	+	---	---	+
	Axial tension	---	---	---	+
	External pressure	+	---	---	+
	Torsion	+	---	---	+
	Combination of bending and axial tension	+	---	---	+
	Combination of external pressure and axial tension	+	---	---	+
	Combination of bending, external pressure and axial tension	+	---	---	+
	Combination of torsion, bending axial tension and external pressure.	+	---	---	+
Operational Loads	Constant internal fluid pressure	---	+	---	+
	Fluctuating internal fluid pressure	---	---	+	+
	Hydrodynamic forces due to internal axial flow	---	---	+	+
	Hydrodynamic forces due to external cross flow	---	---	+	+
	Impact pressure due to fluid hammer	---	---	---	+
	Thermal stresses due to temperature gradient	+	+	---	+
	Uniform elevated temperature effects	---	+	---	+
	Local impact by foreign objects	---	---	---	+
	External pressure due to pipe-soil interaction	+	---	---	+
	Bending due to soil differential settlement	+	---	---	+
	Moisture strain effects	---	---	---	+
NOTE: + means it is included in the design load, while --- means it is excluded in the design load					

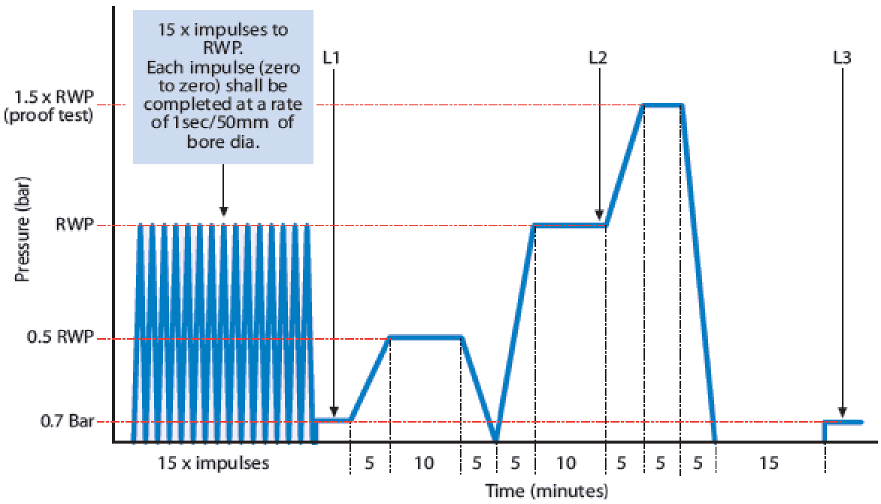

Figure 5 Typical duration for applied pressure on bonded marine hoses in OCIMF recommended hydrostatic pressure test

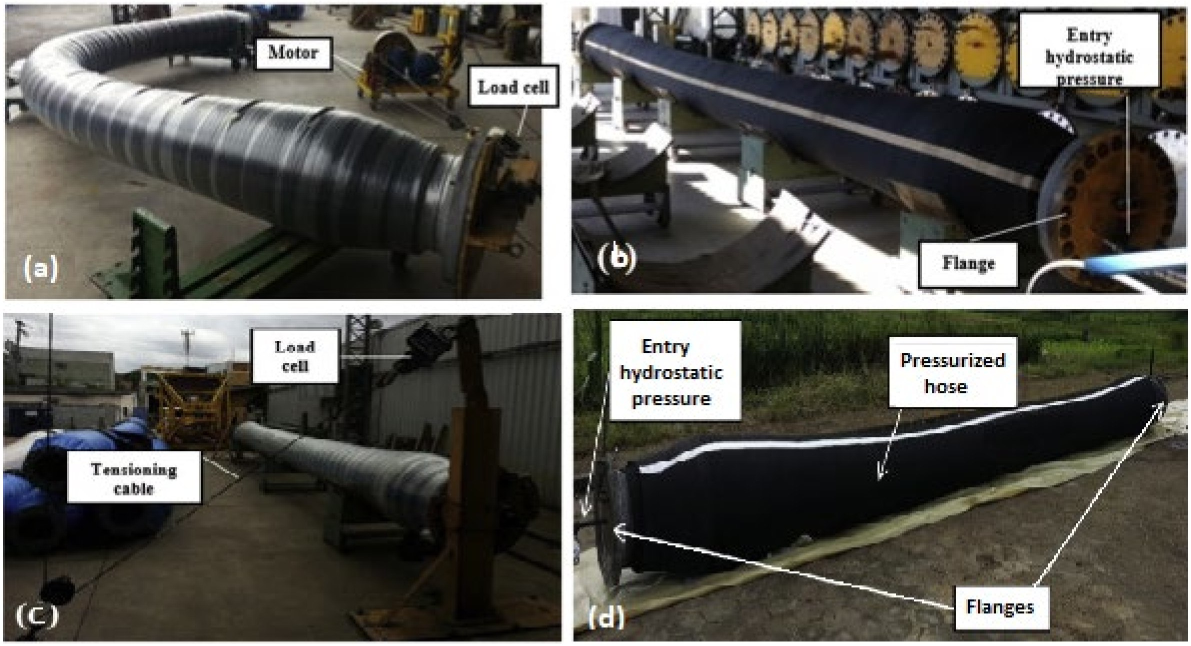

Figure 6 Experimental load tests on hose fatigue from (a) bending, (b) hydrostatic pressure, (c) torsion, and (d) burst. (Reproduced, Hose Courtesy: Tonatto et al. 2017, 2018)

2.5 Suitability and Purchase of Marine hoses

The appropriate selection of offshore hoses to be used on any offshore/marine project is dependent on specific considerations, as summarised in Table 3. These factors include the process route, nearness of the shore, the number of discharge hose-lines required, offshore offloading, storage capacity, the environmental conditions in that ocean or offshore site. An essential aspect of hose design is its suitability and purchase requirements. Every hose manufacturer aims to deliver the best product according to the OCIMF guidelines for bonded marine hoses. As such, it must have high quality to ensure a high volume of hose product sales. The industry recommendation - OCIMF GMPHOM 2009 (OCIMF 2009) standard also covers the purchase of these hoses. Presently, the API (API 2020) database has the following approved hose manufacturers: 4 suppliers with API 17K approved products, 13 suppliers of approved API 16C flexible choke and kill lines, 43 manufacturers of approved API 7K high pressure mud and cement hoses, as presented in Table 4. The details of the service delivered by each of these hoses is presented in Table 5. It is noteworthy that marine hoses have markings imprinted by the manufacturers to show the ratings, specification, and hose nomenclature, as depicted in Figure 7. According to PSA (2018) report, it was avowed that it is the manufacturer's responsibility to document that the product fulfills the requirements. At the same time, it is the purchaser's responsibility to check that the product is suitable for the intended application. However, the supply of GMPHOM 2009 hoses does not require any certification.

Table 3 Offloading hose system selection outcome/option

Options	Name of Type	Selection options on Offloading Systems	Observations
1	Offloading Offshore system lacking buffered storages	Fixed tower mooring systems.	Immersed flexibles (or those submerged) are not required.
		Disconnectable turret mooring systems, Tripod catenary mooring/loading system, Single anchor loading, Floating tower/platform systems, Vertical anchor leg mooring, Catenary anchor leg mooring systems, Articulated loading column/platform, Single anchor leg mooring system, are all available for ships lacking Dynamic Position (DP) systems.	Permanently submerged high-pressure flexibles or universal flowline joints are required for every one of them. Most of these might be used by DP vessels.
		Offshore offloading system, Single leg hybrid riser, Hybrid riser tower and Submerged loading systems, are all available for ships having Dynamic Position (DP) systems.	Each one necessitates submerged high-pressure flexibles or universal flowline joints that are fully immersed in permanent positions.
2	Offloading Offshore system having buffered storages (reconditioning on storage facility)	Storage tanks integrated into the base of Fixed tower mooring systems (FTM).	The amount of storage space available may be restricted.
		Floating storage and offloading (FSO) vessel; Floating storage and processing (FSP) vessel.	Weathervaning storage vessel anchored in permanent positions with tandem transfer mooring
3	Offloading Near-shore to pipe/hose terminals lacking buffered storages	Fits into Fixed tower mooring systems (FTM).	No requirement for submerged flexibles
		Tripod catenary mooring/loading system, Single anchor loading, Vertical anchor leg mooring, Catenary anchor leg mooring systems, Single anchor leg mooring system, are available for every type of ship.	Each of these necessitate the use of submerged high-pressure flexibles. Considering insufficient water depth, systems for DP vessels are specified under Option 1.
		Fits into Conventional buoy mooring (CBM).	Only in sheltered seas should this be used. Perpetually submerged high-pressure flexibles anchored in permanent positions are required.
4	Offloading Near-shore to pipe/hose terminals having buffered storages	Fixed tower mooring systems with storage tanks integrated into base, (reconditioning on storage facility).	The amount of storage space available may be restricted.
		Floating storage and processing vessel, (reconditioned on storage facility).	Weathervaning storage vessel anchored in permanent positions with tandem transfer mooring.
		Fixed tower mooring systems having buffered storages reconditioned onshore or onshore in-situ buffers.	Using rigid pipe-in-pipe for refrigerated liquid transfer to shore storage.

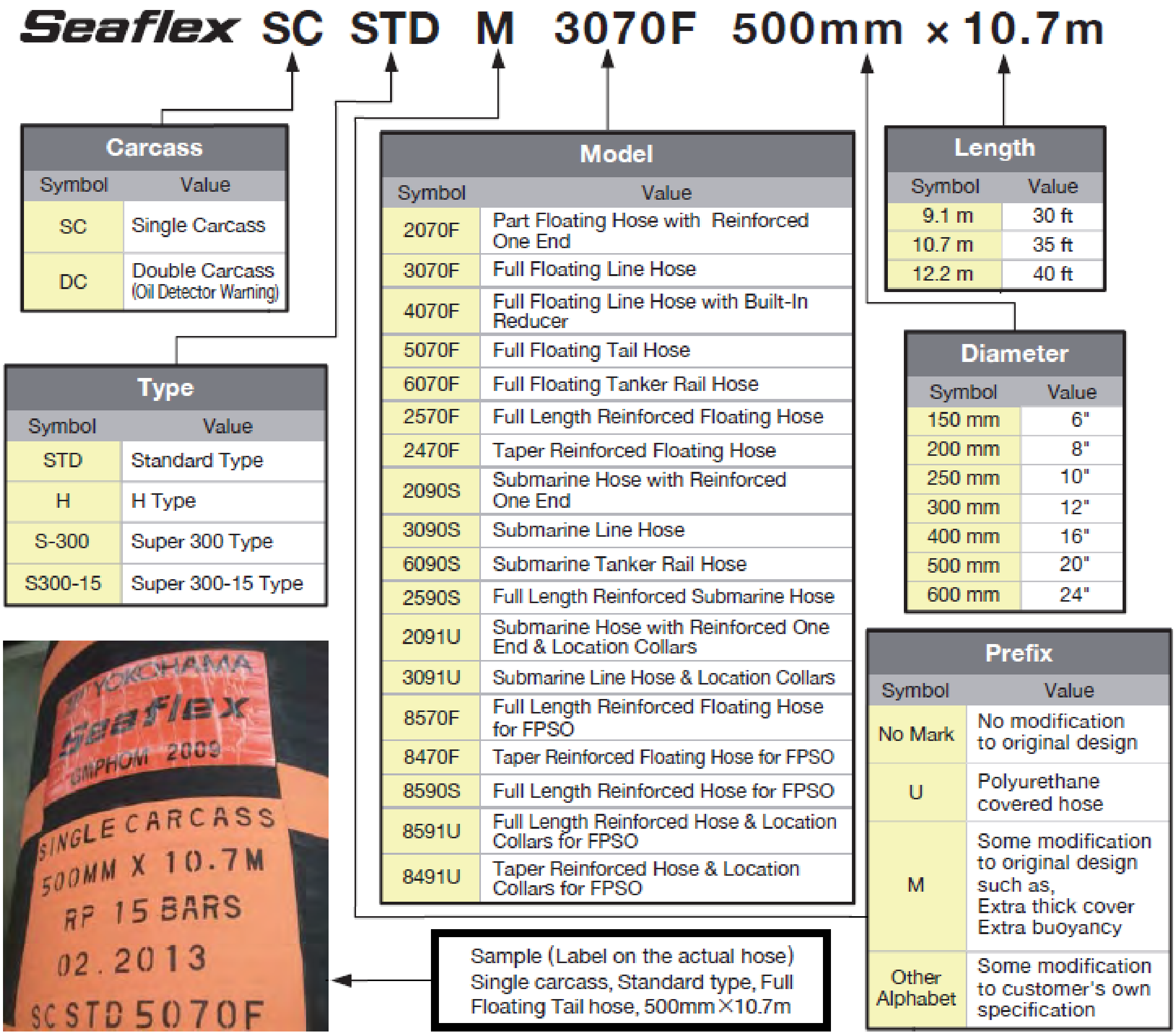

Figure 7 Hose Nomenclature - Example of Seaflex Marine Hose (Reproduced, Courtesy: Yokohama)

Figure 8 Bonga CALM buoy in Nigerian waters located Offshore West Africa (Courtesy: Offshore Magazine).

2.6 Fluid Transfer via Bonded Marine Hoses

The fluid transfer operations of LNG products via bonded marine hoses have received some attention in recent times due to innovative hoses been developed (Gaskill C. et al. 2018, Humphreys, V. et al. 2004, van Bokhorst et al. 2014, Witz et al. 2004). A particular advancement is the hose monitoring systems used for better performance, longer serviceability life and lesser hose failures. The monitoring systems utilise sensors incorporated onto hoses, and other floating offshore structures (FOS). Their functions include sending data on hose tension, CALM buoy heave motion and other gyrometric motion data, such as the CALM buoy in Figure 8. In ocean engineering, environmental factors can have a significant impact on CALM (or SPM) buoy operations. SPM tanker loading movements have a lot of operational requirements. As the vessel's draught grows, the major meteorological and oceanographic (metocean) forces operating on it are likely to shift from wind-induced to surface current. In such cases, it is becoming increasingly important to monitor metocean conditions, as well as the associated stresses on the anchor chain and tanker mooring hawsers at the SPM loading buoys. The information can be utilised to enhance tanker operations, reduce the risk of accidents, and generate site-specific reports to aid future planning. For offshore loading operations, CALM buoys are more commonly used. The tanker approaches the SPM into the dominating force (wind or current), moors to the SPM, and picks up the floating hoses to commence loading, as per conventional berthing practise. In the case of a sudden shift in external forces, a tug pulls the tanker from the stern to ensure it does not ride over the SPM (e.g. wind or current). In practice, marine hose applications have led to advancements in various mooring methods used in fluid transfer. Examples are single point moorings, ship-to-ship hose transfer, and other conventional methods, as shown in Figures 9-10.

During fluid transfer operation, the tanker is empty or partially filled (depending on cargo parcel size) when it initially moors to the SPM and its draught is at a minimum. The angle at which the tanker leans to the SPM is dictated by the wind force, which usually outweighs the current force. As the tanker fills up with oil, its draught rises, and the topsides height drops, thus making the current its dominant force. However, the vectors for current and wind forces often fluctuate in amplitude and direction. This fluctuation alters the tanker's position relative to the SPM. The SPM is obscured from view beneath the tanker's stern, so personnel aboard the tug may not detect the change. Since the SPM is located beneath the tanker's bow, it may not be visible from the bridge. If the tanker moves, there is a risk of a forward collision with the SPM, which could result in damage that prevents unloading while the SPM is repaired. Thus, in certain seas like Nigeria's Bonga Field in Offshore West Africa, such near-surface currents are usually powerful and varies with time and location. These location are also typified with prevalent squall weathers, seen acting on the tanker attached to a CALM buoy or an SPM terminal (Hans H. 2004, Quinnell M. 2006). This buoy facility might be subjected to intense and changing stresses due to the rising waves in the sea and backwashing currents. This is confirmed in studies on CALM buoy hoses (Amaechi et al. 2019a, 2019b, 2021e, 2021f, 2021g). Thus, the inclusion of motion monitoring, response monitoring, tension monitoring, and real-time metocean monitoring sensors are good practice over the past two decades. The system was developed to capture a large amount of raw, high-frequency metocean and tension data. It also helps to conduct detailed future investigations into metocean conditions (e.g., wave steepness, squall monitoring), hose response, and SPM motion (e.g., CALM buoy pitch, roll, and heave), hawser tension (e.g., tanker mooring hawser 'snagging,'), and mooring line tension (e.g., anchor chain tensions). According to Quinnell M. (2006), the 12-m diameter buoy on Total's Djeno field offshore Congo was the first real-time monitoring system Fugro GEOS supplied to a West African SPM in 2004. The next was installed in 2005 on the Bonga field's "Stella," which is one of the world's largest CALM buoys. The Bonga CALM buoy is shown in Figure 8. Surface-recoverable ADCP (Acoustic Doppler Current Profiler) deployment frames are used in most monitoring systems, as are cross-turntable real-time radio modem linkages for all anchor tension and current profile data. They also have a downward-looking ADCP on an SPM, as well as an H-ADCP (Horizontal ADCP) deployed on a rotating turntable to capture near-surface current speed and direction, all of which are adjusted for turntable heading. Monitoring motion changes and material behaviour of the hoses is necessary, as hose strength assessment helps to increase the service life of the SPM (Amaechi et al. 2019a, 2019b, 2021h, 2021i). The risk of colliding with the SPM can be reduced if the tanker pilot can precisely analyse the strength and directions of these forces during approach and connection to the SPM.

Table 4 Manufacturers for various types of bonded flexible hoses and bonded flexible pipes

Specification	Hose Description	Hose Type	No. of Suppliers
API 17K	Bonded flexible risers	Production jumper	1 supplier
API 17K	Crude Oil Loading hoses	Flexible risers	1 supplier
GMPHOM 2009		Challenging offshore loading of crude oil	4 suppliers
EN 1762 (API 17K)	LPG offloading hoses	Offshore and terminal loading of LPG	Over 5 suppliers
EN 1474-2 (API 17K)	LNG offloading hoses	Offshore and terminal loading of LNG	2 suppliers
API 17K	Seawater Intake hoses	Large bore and high strength suction hoses	2 suppliers
API 7K	Hoses for exploration	Rotary hoses Vibrator hoses Cementing hoses	Over 5 suppliers Over 5 suppliers Over 5 suppliers
API 16C		Choke and Kill hoses	Over 5 suppliers
*Suppliers and manufacturers mean the same thing in this context. (Source: PSA 2018)			

Table 5 Summary of industry standard specifications on hoses, the ratings and services

Standard/ Code	Diameter of flexibles	Pressure Rating	Reinforcement		Suction or discharge	Service
			Wire	Textile		
OCIMF GMPHOM 2009	150-600mm (6"-24"NB)	15-21 bar (1.5-2.1MPa)	X	X	Suction & Discharge	Oil
ISO 1403	10-100	<2.5 bar (<2.5MPa)		X	Discharge	Oil
ISO 28017	100-1200mm (4"-48"NB)	<40 bar (<4.0MPa)	X	X	Suction & Discharge	Sea Water, Fresh water, Silt, etc
API 17K	NS	15-21 bar (1.5-2.1MPa)	X	NAS	Discharge	Production Products like oil
API 17B	NS	15-21 bar (1.5-2.1MPa)	X	NAS	Discharge	Production Products like oil
API 16C	50-100mm (2"-4")	15-21 bar (1.5-2.1MPa)	X		Discharge	Choke & Kill fluid
API 7K	50-150mm (2"-6")	15-21 bar (1.5-2.1MPa)	X		Discharge	Mud & Cement
*SWIR Code	500-1000mm (20"-40"NB)	<10 bar [typ.], (<4.0MPa)		Preferred	Suction	Sea water
NB- Nominal bore, NS-Not specified, NAS- Not addressed specifically, SWIR- Sea Water Intake Riser, *SWIR Code – no standard yet						

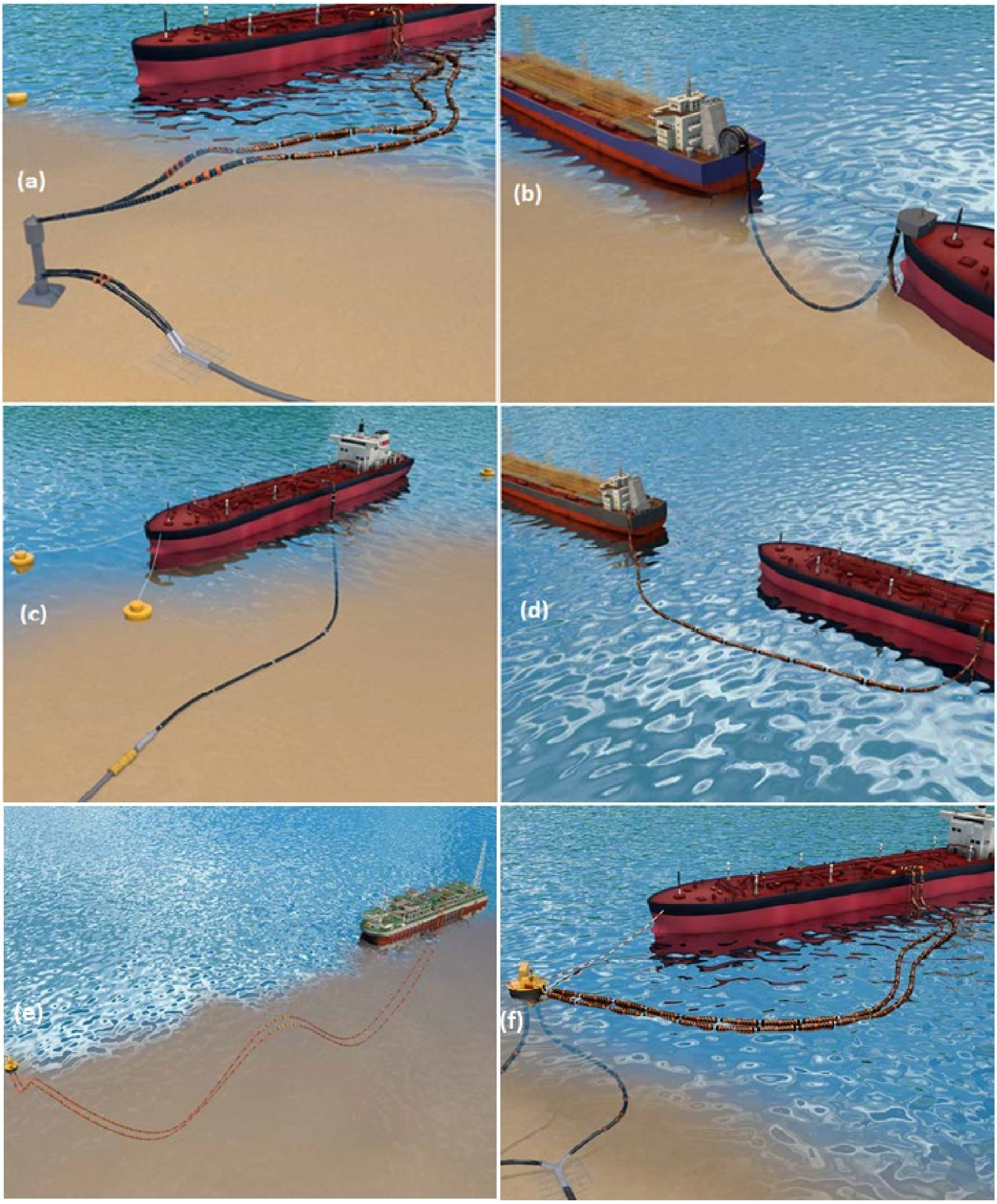

Figure 9 Application of hose (a) Single Anchor Leg Mooring (SALM), (b) Catenary loading system, (c) Conventional buoy mooring (CBM), (d) Floating hose tandem loading, (e)long length midwater systems and (f) Catenary Anchor Leg Mooring (CALM) systems. (Courtesy: ContiTech Dunlop).

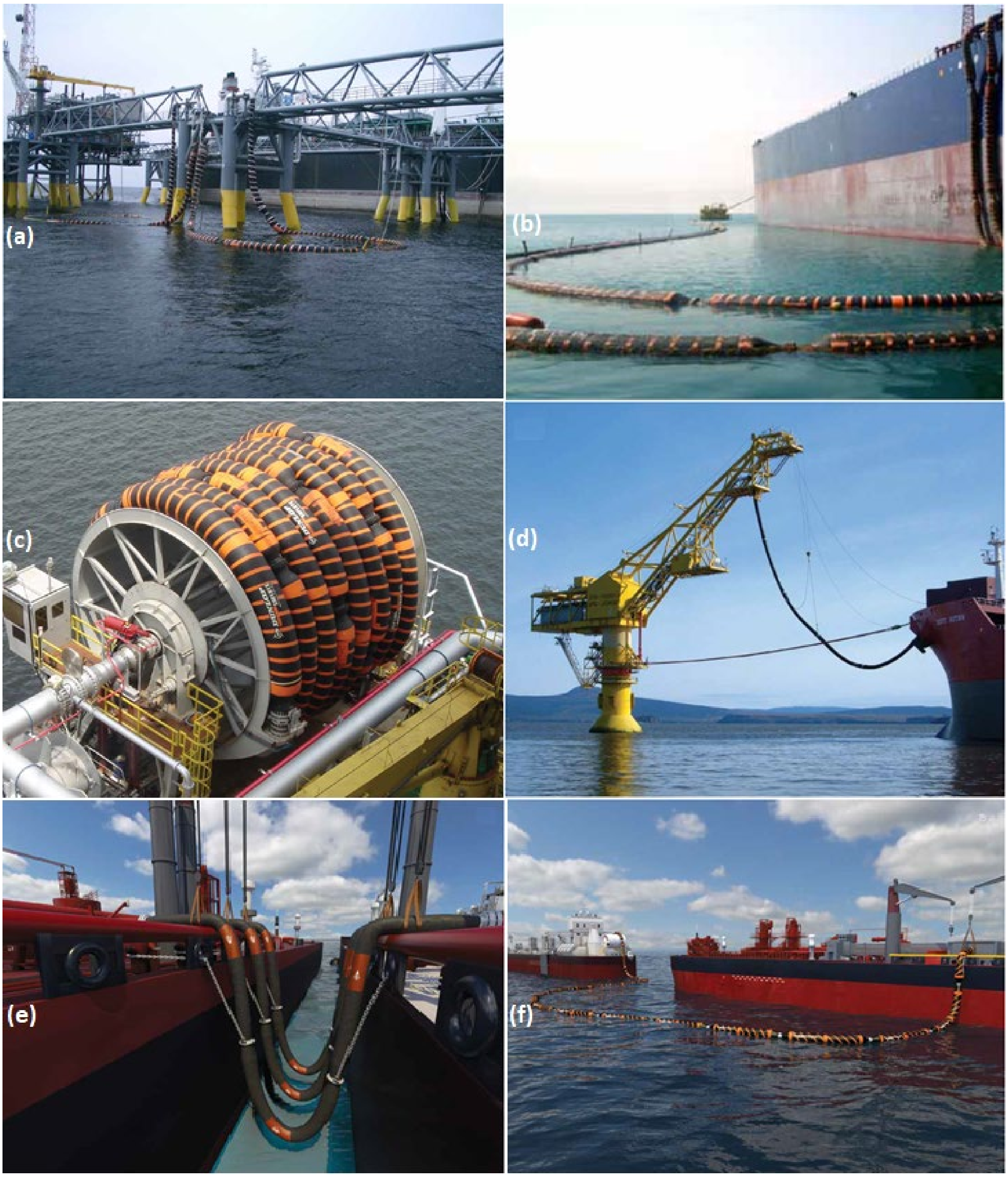

Figure 10 Application of hose (a) Specialist hose for Liquid Petroleum Gas (LPG) transfer, (b) CALM buoy floating hose on FSO, (c) reeling hose (d) specialist hose on soft yoke for tower catenary loading system, (e) API 17k offloading hoses on Yoke, (f) catenary hose on ship-to-ship transfer (Courtesy: ContiTech Dunlop).

3.0 Design Criteria on Bonded marine Hoses

In this section, the design criteria and test methods on hoses are presented.

3.1 Body of Marine Hose

The design criteria for designing marine hoses are conducted based on the hose section. The hose assembly typically consists of vulcanised rubber, reinforced fibre, and a steel fitting at the end. However, due to induced internal pressures and bending forces, marine hoses are prone to failures. On this basis, for effective operations, practical offshore systems with a lot of flexibility are required. This challenge necessitates the use of multi-layered marine hoses that can handle the pressure and moments. Steel helical wire and reinforcing layers are very significant among the available marine hose layers. Gonzalez et al. (2016) modelled a 20" marine hose, with properties in Table 6. Reinforced layers are made up of synthetic fibres with different winding angles in each layer. As a result, the composite layers have several advantages over traditional constructions. Despite creating various structural design recommendations, the difficulties connected with bonded flexible marine hoses have not been adequately investigated. As a result, the theoretical investigation of maritime hoses has received less attention. On the other hand, theoretical studies will overcome the mechanical complexity of the structures by focusing on the primary layers and therefore giving a reference base, according to the researcher.

Zhou et al. (2018) examined reinforced layers in bonded flexible marine hoses that were under internal pressure. They wanted to create a theoretical solution to elucidate the mechanical behaviours of the reinforcement layers and present a mathematical strategy for multi-layer synthetic fibre composites in structures. In the models by Zhou et al. (2018) and Gonzalez et al. (2016), the feasibility and correctness of both methods were confirmed by comparing the results to those found in the literature. Typical mechanical properties of marine hoses are given in Table 7. Distinctive layers of the hose's body can be observed in Figure 11, with material attributes in Table 6. The method enhances the determination of reinforcing fibre layers, giving necessary information for designing the hose. It is valuable guidance during the design, optimization, and verification of the behaviours of marine hoses. As a result, due to the combination of the winding angles, internal pressure, and the number of layers, it was required to explore parameter and failure analyses, which generated distinctly different conclusions. For example, Zhou et al. (2018) obtained a winding angle of ±55 as ideal for their marine hose model. Furthermore, these methodologies considerably lowered the computing time due to programming. Additionally, the post-processed findings could be simplified and then efficiently exported.

Table 6 Material properties of the 20" marine hose (Gonzalez et al. 2016)

Layers	**Particulars**	**Reinforcement**	**Thickness (mm)**	**Cross-sectional area (mm^2)**	**Laying angle**	**Number of fibre filament**	**Number of sheets**
1	Liner-1	---	17.5	---	---	---	---
2	Cord-1	Nylon 66	30.0	0.126	+45°/-45°	29,402	22
3	Bend Stiffener	Stainless steel	23.0	176.71	+88,9°	1	1
4	Cord-2	Nylon 66	15.0	0.126	+45°/-45°	16,827	11
5	Cover	---	5.0	---	---	---	---
6	Cord-3	Polyester	6.0	0.126	+45°/-45°	14,556	2
7	Elastomer-1	---	13.0	---	---	---	---
8	Cord-4	Polyester	40.0	0.126	+45°/-45°	15,421	16
9	Elastomer-2	---	5.0	---	---	---	---
NOTE: ‡ Distance between consecutives fibers cords are 1,05mm; †See layers definitions on Figure 12; Purpose- Offloading/loading							

Table 7 Mechanical properties of the materials used in the 20" marine hose

Material	**Young's modulus (MPa)**	**Maximum elongation (%)**	**Ultimate stress (MPa)**	**Poisson ratio**
Stainless steel AISI 304[1,4]	193,000.00	40.00	520.00	0.29
Nitrile rubber (NBR)[2,4]	6.50	450.00	12.40	0.50
Polyester 120 SMC[3,4]	3500.00	13.00	89.70	0.42
Polyamide nylon 66[3,4]	3500.00	19.00	94.50	0.42
[1]API (2016); [2]Flexomarine (2013); [3]TRELLEBORG (2016); [4]Matweb (2021); † Material modelling, 0.499 used Source: Gonzalez et al. 2016, LACEO (2011) and Chesteron (2020).				

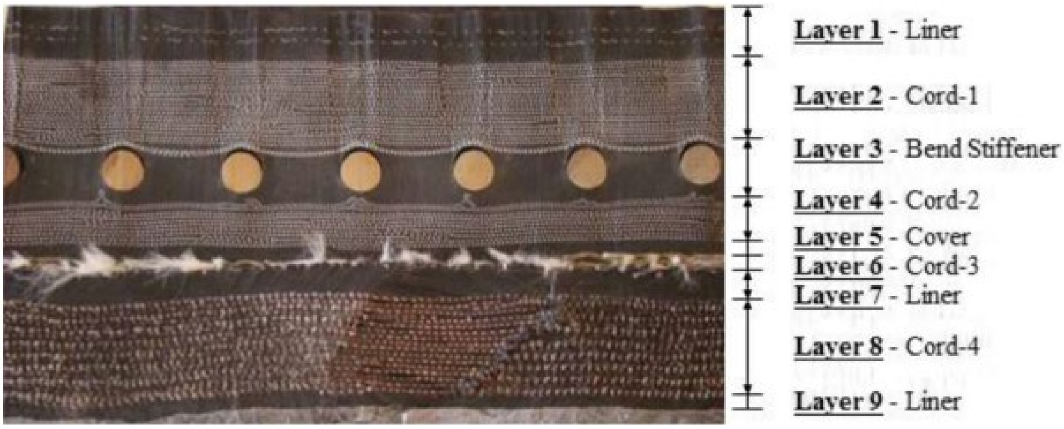

Figure 11 Hose Layer showing the hose cross-section design for hose body modelling (Courtesy: Gonzalez et al. 2016)

3.2 End-Fitting of Marine Hoses

Generally, hoses can be classified based on the application and the pressure loadings. This classification is considered during the design of the body of the hoses and the end-fitting. Figure 11 shows the typical end-fitting and hose body for two marine hoses with the stiffened end. The *GMPHOM OCIMF 2009* (OCIMF 2009) is the industry standard for manufacturing and purchasing marine hoses. It is also the principal guide for designing and testing both loading and discharging hoses. However, since hose manufacturers have other industry specifications, there is no explicit guideline for the design of GMPHOM hose-lines considered but OCIMF (2009). Different studies on end fittings for hoses have been carried out, as illustrated in Figures 11, 13 and 14. A comprehensive investigation on end fitting geometry design and swaging parameter optimization (Cho et al. 2005; Cho and Song, 2007) is pertinent to generate any hose end-fitting (Lee G. C. et al. 2011, Han S.R. et al. 2012, Toh W. et al. 2018). In a numerical study conducted by Lee G. C. et al. (2011) with experimental validation, the leakage path was observed in high-pressure hose assembly, tested using fluorescent material for internal pressure of 15 MPa. In a similar study, Han S. R. et al. (2012) presented a computer-aided engineering (CAE) simulation study on a swagged end fitting geometry optimized for automobile power steering hoses. The design of experiment (DOE) was performed to optimised the model. It was also verified by comparing two different end fittings by experimental tests on 19.8 inches hoses. The results showed that optimized model had some economical savings during production of swaged end fitting. The design philosophy is built on hose serviceability, which should approach 20 years if all set standards are met, including extensive static and dynamic tests for certification. In practice, the service life of marine hoses is typically five (5) years, and preventative maintenance is utilised to evaluate the hose's integrity. Based on the standard, there are typical specifications as follows: (a) Burst test: The inner (first) carcass has a minimum burst pressure of 105 bar, whereas the outer (second) carcass has a minimum burst pressure of 42 bar. (b) Minimum bending radius (MBR): The hose must be able to bear an MBR of six times (6D) its inner diameter for floating hoses and four times (4D) its inner diameter for submarine hoses. (c) Hydrostatic test results: 0.7% maximum permanent elongation and 2.5% maximum transient elongation. (d) Buoyancy: A minimum of 20% buoyancy, with a maximum of 25%–30%; (e) The Inner diameter or bore: Determined by the rate of transmission or transfer rate; (f) Depending on the operational unit, the hose length is 9.3m, 10.7m, or 12.2m. (g) Maximum environmental condition: The storm with annual recurrence is the limit condition used in oil offloading operations. A hundred-year recurrence condition is used for line storage.

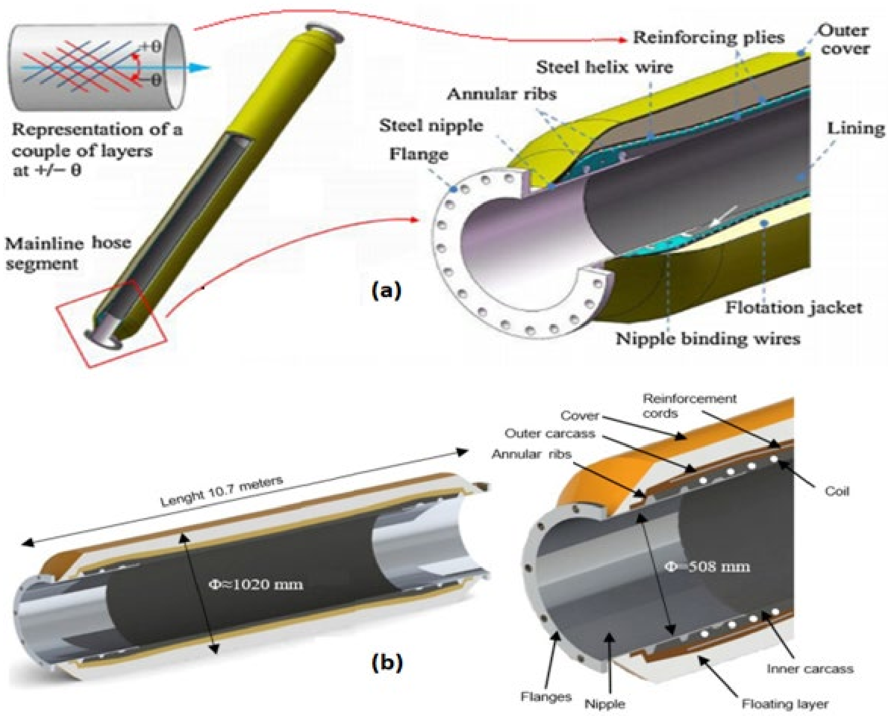

Figure 12 Main parts of stiffened marine hoses (Reproduced; Courtesy: Gao Q. et al. 2018; Tonatto M.L.P. et al. 2018).

3.3 Helix reinforcement of Marine Hoses

The effect of hose reinforcements have been investigated by different studies, in three different design concepts. These concepts are the helical spring reinforcements, the ring reinforcements and the wire braid reinforcements. Miller, J. & Chermak, M. A. (1997) investigated on wire hose reinforcement arranged the proximal and distal braids of a two-wire braid hose being laid across symmetrical angles at $\pm 54.74^{o}$. The authors concluded that the causes of premature hose failures were nonuniform load profile distributed between the proximal and distal braids of the hose layers, minimum bend radius, securement and fitting retention. Entwistle K. M. (1980) investigated hydraulic hoses having braids with steel wire reinforcements, measurements on pressure variation against elastic strain in the wires of the outer braid of the two-braid high pressure hydraulic hose. Another aspect that is very important in the design of the reinforcement in marine hoses is the choice of material. Tonatto et al. (2018) proposed the use of hybrid polyamide/aramid reinforcement cords in a floating hose achieved by considering the hyperelastic effects of nonlinear structural response of the hose. The material and geometry models were included in a 3D meso-scale model in ABAQUS. Using beam elements, the hydrodynamic loads were examined in the macro-scale model to evaluate the hose line forces and the authors found that the hybrid cords showed that they can minimise the hose's internal loads. Hybrid cords offered a 15% weight decrease by reducing the number of layers in the hose compared to regular cords. It also resulted in respective reductions of 21.6% in bending stiffness, 52.2% in torsional stiffness, and 43.9% in specific axial stiffness. It was concluded that the structural response of the hose-line was well predicted by the multi-scale study, and the reduced potential for failure may extend the service life of the hose. The reinforcement in an unloading hose is integrated into the polymer matrix, making it a bonded pipe construction. The liner, reinforcing cords, and coil make up the inner carcass, which is responsible for fluid containment under normal working conditions. The liner should therefore endure close contact with oil hydrocarbons, the reinforcement cords give the hose strength and stiffness, and the coil, which is often constructed from steel, must withstand crushing effects on the construction. The outer carcass is made up of liner and reinforcing cords, and its primary function is to prevent liquids from leaking into the environment if the inner carcass fails. The hose also has flanges at the end fittings to facilitate connecting with other hoses, as well as a floating layer to provide buoyancy. A typical hose sections and marine single/double carcass hose used for unloading operations is shown in Figures 8 and 9, respectively. In current hose developments, the aromatic polyamide structure, which consists of poly (m-phenylene isophthalamide) (like Nomex®) and poly (p-phenylene terephthalamide) (like Kevlar®) with over 85% of the amide groups explicitly connected by two aromatic rings, is a more current material for the cords used to reinforce elastomers in a variety of hoses Seretis et al. (2015). However, these polymeric fibres possess outstanding aggregate qualities. As Zandiyeh (2006) points out, the service life of hoses whereby a pure Kevlar cords are exposed to compression load is decreased relative to hybrid cords, producing a decent distribution of attributes. Onbilger et al. (2008) found that hybrid cords containing two Kevlar and one nylon yarn have better compression fatigue capabilities than pure 3-yarn Kevlar cables in another study. Tonatto et al. (2017) and others have found kink bands forming caused by a lack of transverse reinforcement in between strongly orientated polymeric chains, resulting in strength reduction upon compressive fatigue (Onbilger et al. 2008, Leal et al. 2009, Seretis et al. 2015, Tonatto et al. 2017).

Lassen T. et al. (2014) conducted another major study on the load response of offshore hoses, which included numerical FE modelling and experimental test on a 20" bonded hose having end-fittings of steel. The study includes limitations for extreme load capacity assessments for full-scale tests based on API 17K standards. For the bonded loading hoses subjected to bending, tension and high pressure under catenary design, a fatigue life prediction methodology was developed, as well as repetitive reeling under high hose tension. The current study emphasises the load impacts upon the hose subjected to reeling loads, as well as the prediction methods for the fatigue life considering the rubber and steel components. According to their investigation, the highest helix diameter change achieved the acceptable value of 1% at a tension of 750 kN excluding cradles on the reel. After the cradles were installed, the mid-section helix diameter change for Hose1 reached 1.8% after an applied tension of 1200 kN and subsequent unloading. In contrast, the diameter change for Hose2 was close to 1.7% after the same applied tension, as some of the diameter modification was due to the initial test cases excluding cradles. The authors believe that in service for a hose permanently placed in a cradle position, the local peak strain in the helix will not be this high, but that the local peak strain in the helix was 17,000s at the 12 o'clock location at an applied tension of 1200 kN; and that an applied tension of 750 kN is permissible, based on the API 17K and API 17B requirements. As a result, an increasing trend in tension beyond this level on a hose supported by cradles will retain its integral functionality. However, after applying a tension of 1200 kN, final ovalisation will approach

1.8%. Their study proved permissible from a structural integrity standpoint. Still, it did not conform to the API 17K's low usage criteria called the Utlilization Factors (UF), as such will become an issue during repeated reeling.

3.4 Utilization of Marine Hose materials

Different studies have been carried out on the materials used for manufacturing hose and optimizing offshore hoses, as presented in Sections 3.1-3.3. Different designs were also carried out on marine hoses, both in the designs such as Trelleborg's single and dual carcass end fittings in Figures 13(a-b) and the finite element analysis of end fitting in Figure 14(c-d). The finite element models are used to obtain the hose end-fitting stress profiles. These profiles can used to ascertain the strength behaviour, fatigue or failure of the hose. This assessment can be achieved by using utilization factor (UF) or Safety Factor (S.F) as a limit. Both U.F and S.F can also be used to ascertain the amount of material used in a section of the hose, such as between the mainline and the reinforced end of the hose (Amaechi C.V. et al. 2019a, 2019b, 2019c). When analysed, the stress loading factors (SLF) in Figure 15(a) show the highest tension of 51 in SLF and the highest bending of 42 in SLF, which occurs in the ring-in-bumper profile. The utilization matrix (UM) in Figure 15(b) shows a maximum UM of 0.372 in rubber utilisation. It can be observed that rubber has the highest utilization matrix of 0.372 in comparison to other hose materials. Next to the rubber is the ring and the lamella. However, since the ring-in-bumper has the highest tension and bending stress loading factors, it shows that it experienced more loadings in the hose structure (Antal D. et al. 2001, 2003, 2012). Thus, it is essential to model the hoses correctly. Hose materials can also differ, such as the hose reinforcements can be rings and spirals, and the hose covers can be smooth, corrugated or gimbals.

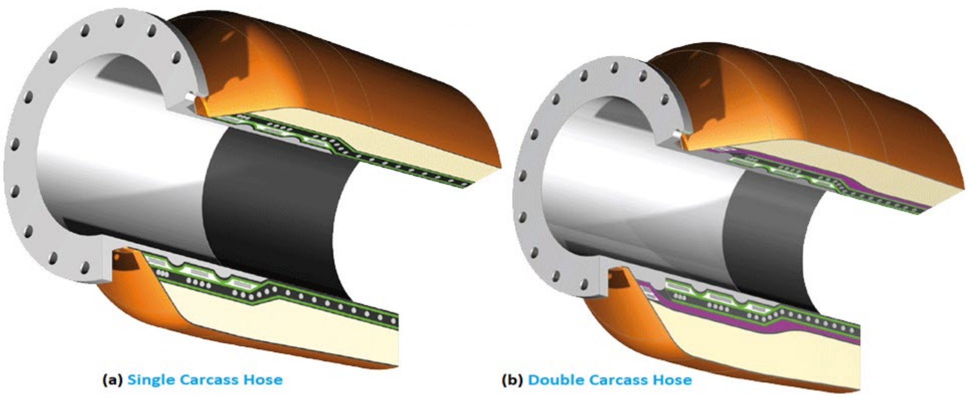

Figure 13 Hose designs showing (a) single carcass hose, (b) dual/double carcass hose, (Reproduced, Courtesy: Trelleborg)

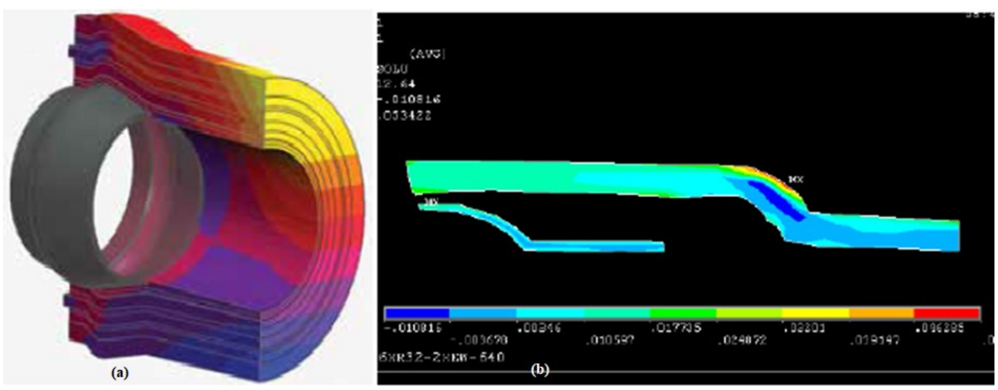

Figure 14 Finite element analysis of bonded marine hose with end-fitting

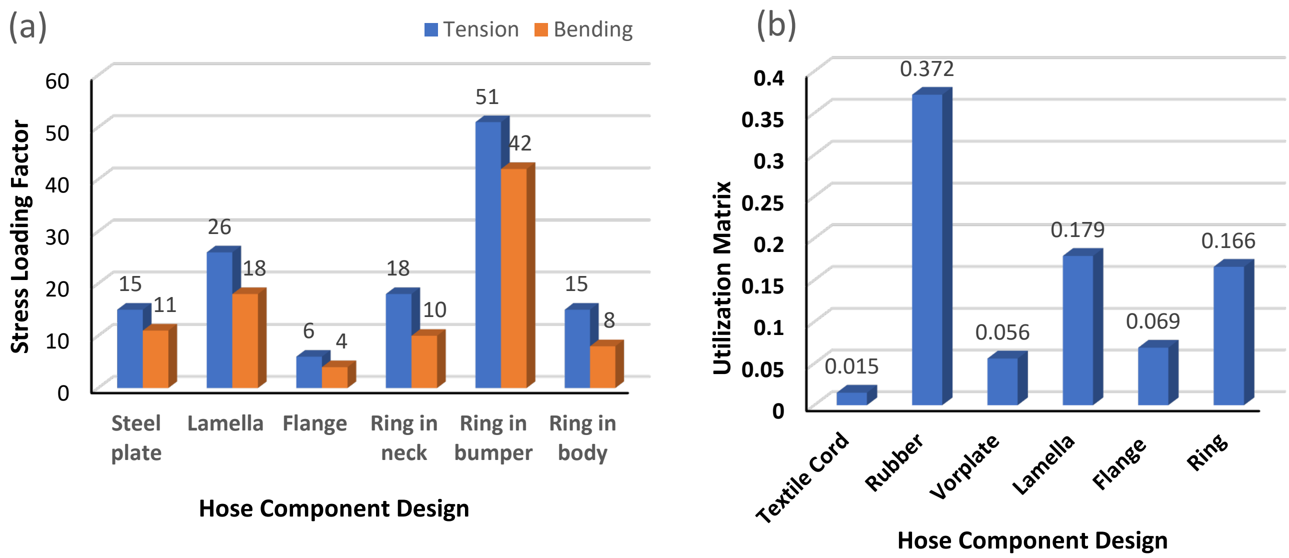

Figure 15 Offshore hose design (a) Stress loading factors and (b) Utilization matrix (Antal D. et al., 2012)

Table 8 Standards, handbooks and guidelines on marine hoses and related systems

Standards / Guideline	**Title**
OCIMF 2009, 5th Ed.	Guide to manufacturing and purchasing Hoses for offshore moorings (GMPHOM), 2009
OCIMF 1995	Guideline for the Handing, Storage, Inspection and Testing of the Hose
OCIMF 1991, 4th Ed.	Guide to purchasing, manufacturing and testing Hoses for offshore moorings
SMOG OCIMF 1995	Single Point Mooring Maintenance and Operations Guide (SMOG), 1995
OCIMF 2000	Guidelines for the purchasing & testing of SPM hawsers
OCIMF 1997	Recommendations for equipment employed in the bow mooring of Conventional tankers at Single Point Moorings
OCIMF 2019	Dynamic torsion load tests for offshore hoses: An update to the Guide to manufacturing and purchasing Hoses for offshore moorings (GMPHOM 2009), section 3.4.10.3
ISO 13628-11: 2007	Flexible pipe systems for subsea and marine applications.
ISO 3821: 2019	Gas welding equipment — Rubber hoses for welding, cutting and allied processes
ISO 1307: 2006	Rubber and plastics hoses — Hose sizes, minimum and maximum inside diameters, and tolerances on cut-to-length hoses
ISO 1403: 2019	Rubber hoses, textile-reinforced, for general-purpose water applications — Specification
ISO 28017: 2018	Rubber hoses and hose assemblies, wire or textile reinforced, for dredging applications — Specification
ISO 7840: 2021	Small craft — Fire-resistant fuel hoses
ISO 15156-3: 2020	Petroleum & natural gas industries- Materials for use in H_2S-containing environments in oil & gas production
ISO 2006 (& API 2006)	Rubber latex, synthetic — Determination of mechanical stability — Part 1: High-speed method
EN 1762: 2018	Rubber hoses and hose assemblies for liquefied petroleum gas, LPG (liquid or gaseous phase), and natural gas up to 25 bar (2,5 MPa) - Specification
EN 1474-1:2009	Installation and equipment for liquefied natural gas - Design and testing of marine transfer systems Part 1: Design and testing of transfer arms
EN 559: 2003	Gas welding equipment - Rubber hoses for welding, cutting and allied processes
EN 1762-1: 2017	Rubber hoses and hose assemblies for liquified petroleum gas, LPG, and natural gas up to 25 bar.
EN 1762-2: 2017	Installation and equipment for liquified natural gas – Design and testing of marine transfer systems – Part 2: Design and Testing of transfer hoses
BS EN 1765-TC: 2020	Rubber hose assemblies for oil suction and discharge services — Specification for the assemblies
BS EN 12115: 2021	Rubber and thermoplastics hoses and hose assemblies for liquid or gaseous chemicals - Specification
BS EN ISO 16904: 2016	Petroleum & natural gas industries - Design and testing of LNG marine transfer arms for conventional onshore terminals
ANSI/ NACE MR0175/ ISO 15156-2015	Selection and qualification of carbon and low-alloy steels, corrosion-resistant alloys, and other alloys for service in equipment in oil and natural gas production and NG treatment plants in H2S-containing
API 17B	Recommended practice for unbonded flexible pipe, 4th ed.
API 17J: 2014	Specification for unbonded flexible pipe, 5th ed.
API 17K	Specification for bonded flexible Pipe
API 16C	Specification for Choke and Kill Systems
API 7K	Specification for drilling and well servicing equipment
DNVGL-RP-115: 2015	Pre-commissioning of submarine pipelines
DNVGL-RP-119: 2015	Thermoplastic composite pipes
DNVGL-OS-E403: 2015	Offshore loading units- Rules and
DNVGL-CP-0183	Flexible hoses - Rules and standards
4Subsea, NTNU, Marintek	Handbook on design and operation of flexible pipes (Fergestad et al. 2017)
MERL &HSE (HSE 2005)	Elastomers for fluid containment in offshore oil and gas production: Guidelines and review.

3.5 Standards on Marine Hose

The development of standards and design specifications on marine risers have received entirely sustainable progress. Currently, there are industry-acceptable standards for most bonded marine hoses, but some are still pending acceptance in the market. These include bonded marine hoses with high percentage of composite materials. As such, the hoses with high composites mixed with elastomers are still under some qualification. A list of some related standards on bonded marine hoses currently in circulation is presented in Table 8. Generally, most marine hoses have standards, except the sea water intake riser (SWIR) hoses. These recommendations and related standards cover their design, as with other types of hoses. However, it does not cover SWIR in totality, so there is the need to elaborate a standard that considers SWIR hoses (Craig 2016, Katona et al. 2009).

3.6 Factory Acceptance Test (FAT)

The factory acceptance test (FAT) requirements for testing bonded marine hoses are prepared based on design practice and field performance. Within the specifications of API 17K, the FAT that can be carried out on flexible pipes, composite risers, and bonded marine hoses are summarised in Table 9. These tests are essential in the design and manufacture process for these flexibles. However, some FATs are based on a request, while others are mandatory requirements. While there is a considerable body of research on bonded marine hoses and composite tube assessments under various load applications, investigations on the Metal Composite Interface (MCI) are still restricted. A related test result of the end-fitting design for composite riser joint, similar to that of marine hoses, was presented by Cederberg (2011) of Lincoln Composites. A general-purpose FE code was used to describe composite and steel components, and their interaction was characterised by a surface contact. Cederberg (2011) published experimental and numerical assessments of a composite riser joint, which included the MCI for an autofrettage pre-stressing stage and a FAT. Following FAT and autofrettage, both pressures and tension were applied in five steps: a) pulling the steel pipe in an axial direction; b) applying internal pressure at a level greater than its yielding strength; c) removing the internal pressure; d) reapplying the pressure at a lower level; and e) releasing the pressure. Figure 16 shows the stress–strain responses of the CFRP tube and steel pipe (X80) for each phase. During autofrettage and FAT, the material responses anticipate a high hoop stress and a relatively reduced axial stress for the composite layers. An interference fit between the steel and composite components is established at the end of the autofrettage stage, leaving the composite tube in tension and the pipe in compression.

Table 9 API 17K recommended factory acceptance tests (FAT) on flexibles (flexible pipes, composite risers, bonded hoses)

Test	Without cathodic Protection		With cathodic Protection		Observations
	With Carcass	Without Carcass	With Carcass	Without Carcass	
Hydrostatic Test	X	X	X		
Electrical Resistance Test			X		
Electrical Resistance Test			X	X	
Electrical Continuity Test			X		
Gauge Test	X		X		
Vacuum Test		X		X	Upon request
Kerosene Test		X		X	Upon request

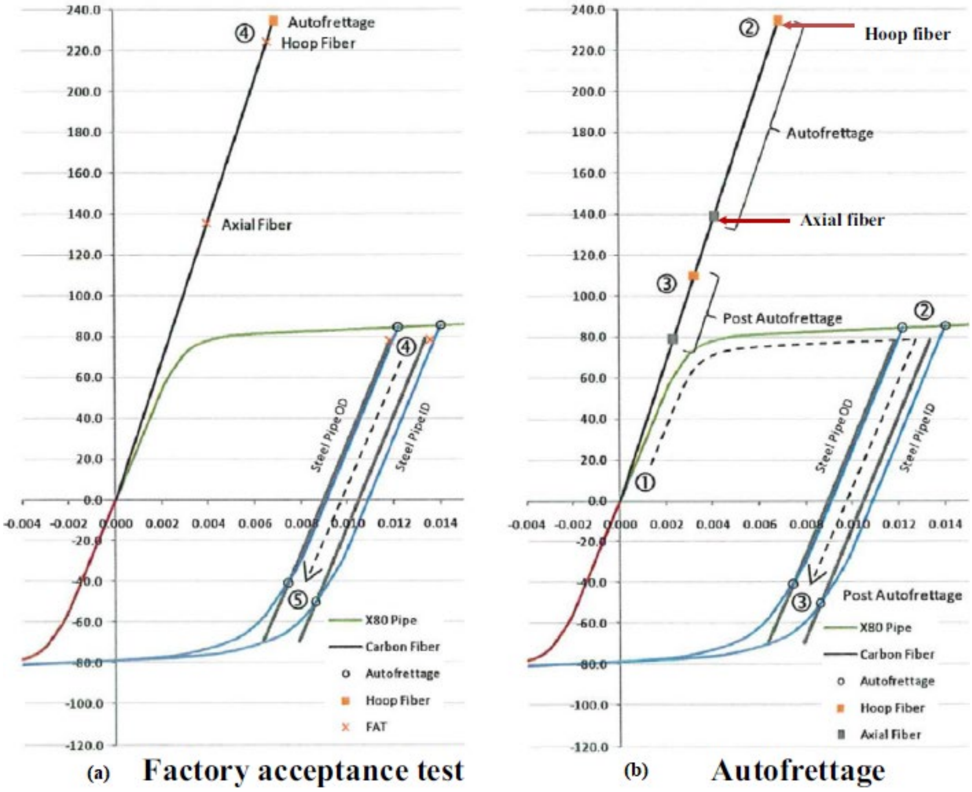

Figure 16 Stress–strain profile of composite pipes vs steel material for (a) FAT and (b) autofrettage tests (Cederberg 2011).

4.0 Mechanical Behaviour Model of Marine Hoses

4.1 Models on Rubberised Marine Hoses

Different models related to rubberised marine hoses or stiffened rubber hoses are based on rubbers and elastomers. Rubbers are usually made from a long chain of molecules known as polymers (Ali et al., 2010), while elastomers are a combination of elastic and polymeric materials (Smith, 1993). Rubber materials are utilized on hoses due to the high elastic properties, flexibility, extensibility, durability, and resilience. In addition, it can endure massive strains of up very high percentage without fracture or deformation occurring permanently (Mars, 2002, Ali A. et al. 2010), as such it has good application (Milad. M. et al. 2017, Abashio A. et al. 2016, Gao Q. et al. 2018). Elastomers have complicated mechanical behaviour. High plastic/plasticity properties, large deformations, stress softening and viscoelastic qualities, are all characteristics of elastomers that go beyond the linear elastic theory. (Naser et al., 2005; Chagnon et al., 2004; Ali A. et al. 2010). Other effects such as the Mullins effect or Stress softening has been reported to exist during initial loading. However, the strain energy function is used to account for residual strains in rubber, as detailed in some literature (Cheng & Chen, 2003, Dorfmann & Ogden, 2004; Horgan et al., 2004). Different constitutive rubber models were reviewed in literature (Ali et al. 2010, Boyce & Arruda 2000), as they differ from composite materials (Amaechi et al. 2019a, 2019e, 2019f). Ali et al. (2010) compared five models for explaining deformation behaviour with experimental data, while Boyce & Arruda (2000) compared models among several rubber models. Boyce & Arruda (2000) and Seibert & Schoche (2000) examined six alternative models for describing deformation behaviour with experimental data (2000). Approaches to deduce rubber's stress-strain attributes from various other idealised models macromolecularly based on statistical or kinetic theory. According to Yeoh & Fleming (1997), the phenomenological theories solves the condition relying upon continuum mechanics rather than molecular theories. Markmann & Verron (2006) comparatively studied rubber-like materials using twenty hyperelastic models and graded these based on fitting it with experimental data.

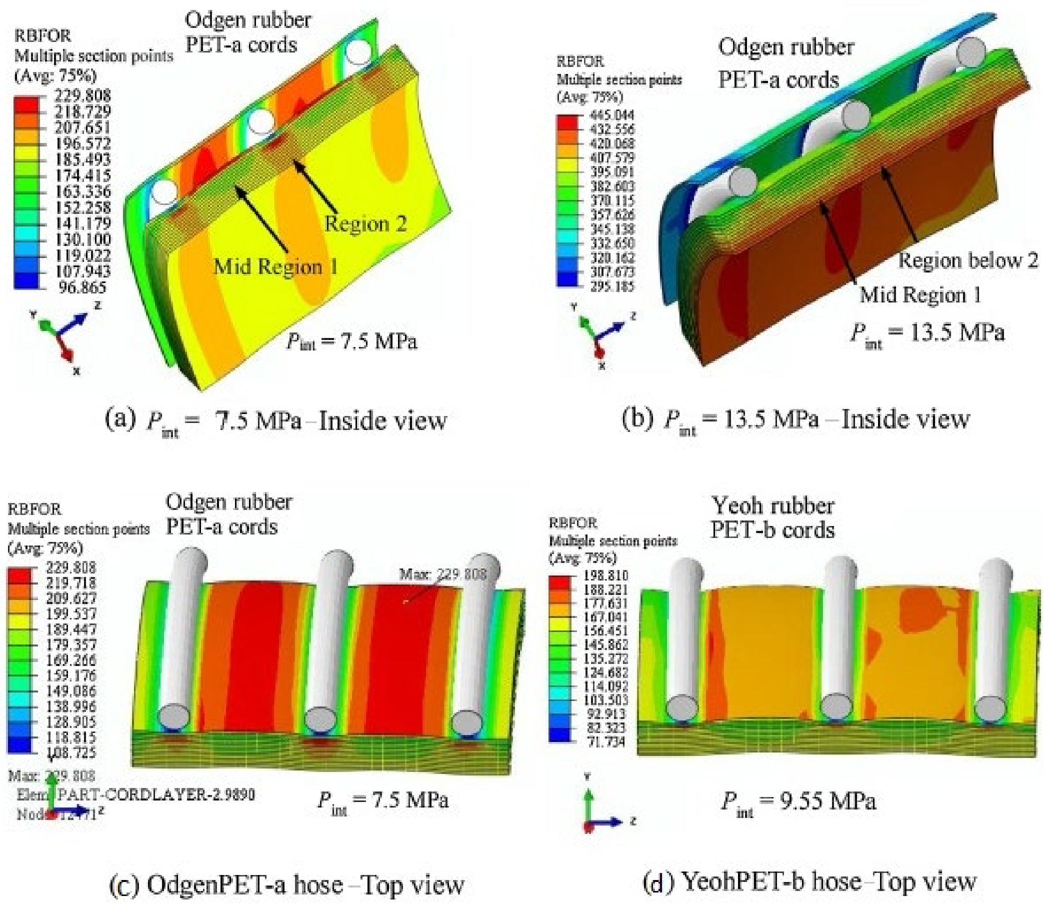

Figure 17 Load in cords at failure pressure at 7.5MPa and 13.5MPa (Reproduced, Courtesy: Gao Q. et al. 2018).

In a study by Gao Q. et al. (2018) on rubber hoses, the Arruda-Boyce fitting model had highest stress, as shown in Figure 17(a) while the Test-PET-a model had highest load-strain curve as shown in Figure 17(b). These models were used to investigate the hyperelasticity of the rubber material, however, hardening factor could also be applied in modelling the rubberised hoses. The 3D FE model, presented in a recent research by Tonatto et al. (2017), was updated to analyse torsional stiffness, bending stiffness and axial stiffness of the hose line, as well as undertook strain and stress evaluations, using a central piece of the hose in Tonatto et al. (2018). Reinforcements and elastomer were evaluated, using hyperelastic model parameters in Tonatto et al. (2017), with the Marlow's model for reinforcing cords and the Arruda Boyce's model for elastomer layers. The micromechanical parameters used in Arruda Boyce's model were: $D = 6.43e^{-3}$, $\lambda_m = 4.05$, $\mu_0 = 0.622$ and $\mu = 0.599$. The Marlow's model, relied on experiments on the reinforcing cord samples, as represented in Figure 17(c). With a sample length of 750 mm, load/length against strain curves were constructed. Using the yield stress of 725 MPa, a Poisson's ratio of 0.3, a Young's modulus of 140 GPa, the steel coiled helix was represented as possessing isotropic attributes. In the uniaxial and wide-strip tension tests conducted on the carbon-black filled vulcanised PVC/nitrile compound of fibre-reinforced composite and nylon cord fabric with two-directional warp and weft by Milad M. et al. (2018), the micromechanical properties considered in the hyperelastic model include: Ogden N1 with $\mu_1 = 18.60$, $\alpha_1 = 25.0$,

$\mu_1 = 8.31$, $\alpha_1 = 13.50$; while Yeoh N2 with $C_{10} = 4.31$, $C_{20} = 18.66$. It was concluded that over the extended regimes tested, the Yeoh and Ogden correlation was shown to best model the experimental data, resulting in the best agreement between experimental data and numerical fit, as shown in Figure 3 (d). In summary, hyperplastic models have been utilised for modelling the rubber materials in recent times, such as rubberised models in Figure 18 for Odgen rubber and Yeoh rubber subjected to burst loads and performed well. This is because these offshore rubberised hoses have both composite materials and rubber materials, as such, hyperplastic models are highly utilized on marine hoses as they correctly model the performance of the hoses (Svein Are Løtveit, 2009, 2018, Tonatto M. et al. 2018, 2019, 2020).

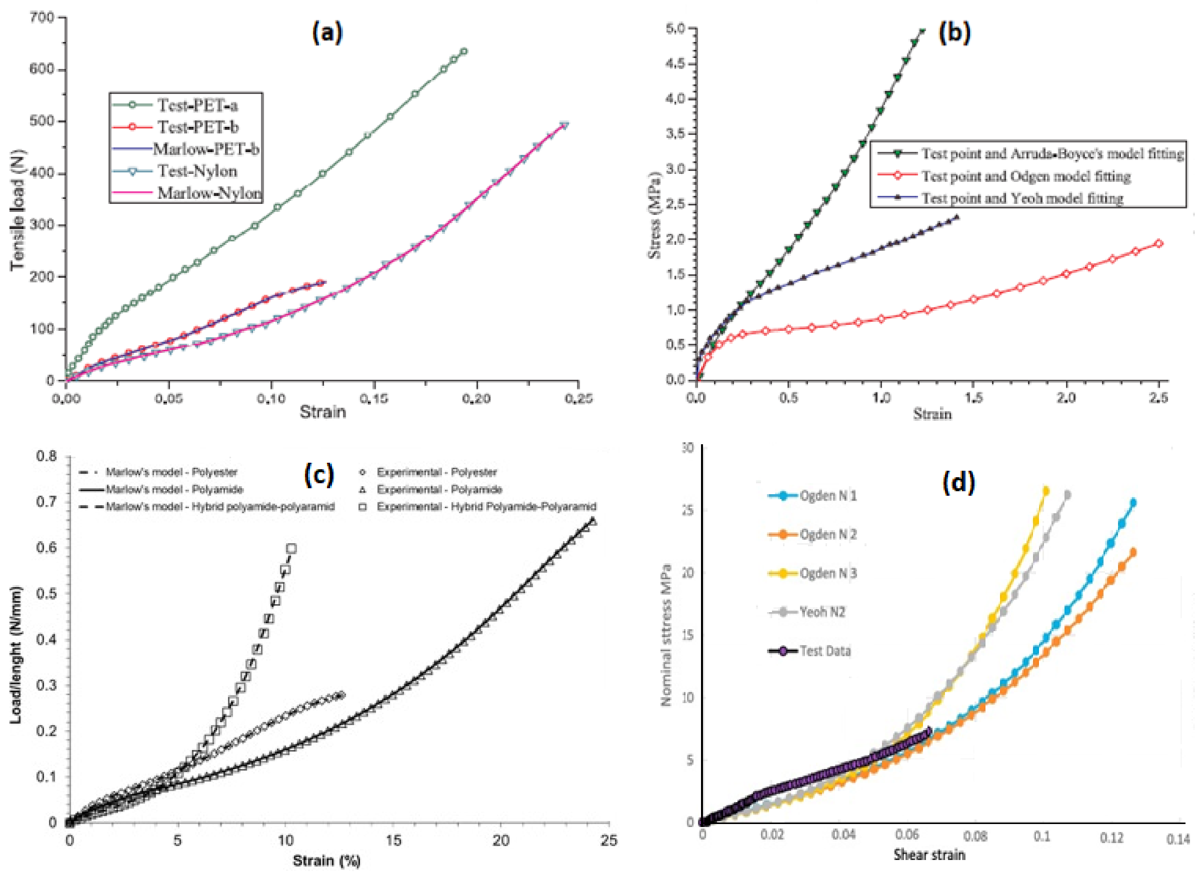

Figure 18 Plots showing (a) stress-strain curves of different rubbers and respective model fitting, and (b) load-strain curves of hyper-elastic fibers, (c) hyperelastic models loaded in weft direction, and (d) hyperelastic curves of the reinforcement chord (Courtesy: Gao Q. et al. 2018, Tonatto M.L.P. et al. 2018, Milad M. et al. 2018)

4.2 Hose Bending and Lateral Deflection

Different studies have been conducted on the material modelling of marine bonded hoses (Gonzalez et al. 2016, Zhou et al. 2018, Tonatto M. et al. 2018, Amaechi et al. 2021a, 2021d). These are similar to material modelling of composite marine riser modelling, except different in material hardening models and rubber models for the elastomers (Amaechi et al. 2019a, 2019b, 2021m, 2021o, 2021p). Thus, the mechanics of the hose-string is considered here, based on hose motion behaviour (or dynamics). The lateral stability of these hoses have already been considered in a study by Huang and Leonard (1989, 1990). However, this review will discuss the hose bending and lateral deflection aspect. In the case of the terminus at point A in Figure 19, the distance is x=0. We have an asymptotic connection as the submarine hose-strings change due to wave and vibration motions. Equation (1), which describes the motion at the end of the hose-string, which yields Equation (1);

$$u(x=0) = a_h \cos \sigma t \tag{1}$$

Where a_h is the amplitude of the buoy motion, σ is the circular frequency of the wave, ω is the angular frequency, k is the wave number. This equation is only real, when there is a steady harmonic motion that is relative to the configuration that can be represented straight and lateral to the buoy when it is positioned deeply backwards. Thus,

$$u(x=0) = a_h(1-\cos \sigma t) \tag{2}$$

Consider a beam model with an element having the forces and moments with longitudinal displacement u, and lateral displacement w, as depicted in Figure 26. The equations of motion along x-direction and z–direction can be represented as in Equation (3).

Along the x-direction, the equation of motion is:

$$S\theta - [S + \left(\frac{\partial S}{\partial \theta}\right) d\theta](\theta - d\theta) = mRd\theta \frac{\partial^2 u}{\partial t^2} \tag{3}$$

Diving both sides by dΘ, and simplifying gives:

$$S - \left(\frac{\partial S(\theta + d\theta)}{\partial \theta}\right) = mR \frac{\partial^2 u}{\partial t^2} \tag{4}$$

Along the z-direction, the equation of motion is:

$$-S + [S + \left(\frac{\partial S}{\partial \theta}\right) d\theta] = mRd\theta \frac{\partial^2 w}{\partial t^2} \tag{5}$$

Diving both sides by dΘ, and simplifying gives:

$$\left(\frac{\partial S}{\partial \theta}\right) = mR \frac{\partial^2 u}{\partial t^2} \tag{6}$$

Taking moments about the edge of the elements in LHS:

$$M - \left[M + \left(\frac{\partial M}{\partial \theta}\right) d\theta\right] + \left[S + \left(\frac{\partial M}{\partial \theta}\right) d\theta\right] Rd\theta = 0 \tag{7}$$

Diving both sides by dΘ, and simplifying gives:

$$-\left[\left(\frac{\partial M}{\partial \theta}\right)\right] + SR + \left[\left(\frac{\partial S}{\partial \theta}\right) d\theta\right] = 0 \tag{8}$$

As δS limits to 0, gives:

$$\frac{\partial M}{\partial \theta} = SR \tag{9}$$

Applying Beam Bending Theory, gives:

$$\frac{M}{EI} = \frac{1}{R} = -\frac{\partial^2 z}{\partial x^2} \tag{10}$$

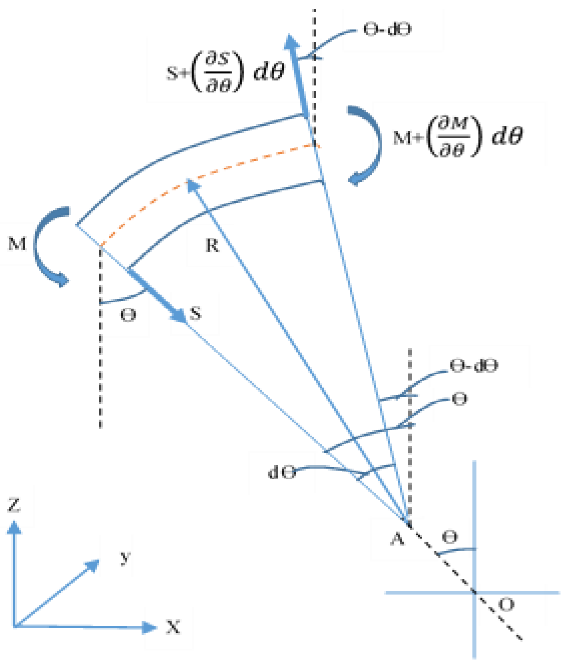

Figure 19 A displaced beam element showing moments and forces

Applying the hose modelling method by O'Donoghue (1987) by assuming that $\theta = \frac{\partial z}{\partial x}$, $Rd\theta = dx$, and w = z; and applying these into Equations (9) and (10), the equation of motion along the longitudinal or x-direction, gives rise to Equation (11) and the lateral or y-direction in Equation (12):

$$EI\,\frac{\partial}{\partial x}\left(\frac{\partial^3 z}{\partial x^3}.\frac{\partial z}{\partial x}\right) = m\,\frac{\partial^2 u}{\partial t^2} \qquad (11)$$

$$EI\,\frac{\partial^4 y}{\partial x^4} + m\,\frac{\partial^2 y}{\partial t^2} = 0 \qquad (12)$$

Equation (12) gives the equation of motion for beam bending for the lateral deflection z(x,t) along the length of the beam section. While Equation (11) presents the longitudinal motion of the beam, with the point of force applied at only x = 0, which is position on the beam model for the free lateral vibration's inertial end condition.

4.3 Hose Snaking Phenomenon

The CALM buoy and the associated hoses are also affected by hydrodynamics. When the hose-string is subjected to induced hydrodynamic forces, the hose will bend. It will bend on the water surface if it is a floating hose, but it will bend inside the water body if it is a submarine hose. The damping force is the proportionate part of the hydrodynamic force to hose velocity, whereas the additional mass force is proportional to acceleration. The damping force and additional mass force components along the z-axis were modelled respectively using the Euler beam approximation, as $(-Q\frac{\partial z}{\partial t})$ and $(-C_a m\frac{\partial^2 z}{\partial t^2})$, where the damping constant is denoted by Q and the coefficient of added mass is C_a. By applying these terms into Equation (12); thus yields:

$$EI\,\frac{\partial^4 y}{\partial x^4} + Q\,\frac{\partial z}{\partial t} + (1 + C_a)\,m\,\frac{\partial^2 z}{\partial t^2} = 0 \qquad (13)$$

In the same line with the Euler beam approximation, the hydrodynamic damping and added mass forces is seen as insignificant to the contribution of the inertial end condition.
However, O'Donoghue (1987) defined C and K with Equations (14) and (15);

$$c^2 = \frac{EI}{(1+C_a)m} \qquad (14)$$

$$K = \frac{Q}{EI} \qquad (15)$$

By applying Equation (12), the equation of motion becomes:

$$\frac{\partial^4 z}{\partial x^4} + K\frac{\partial z}{\partial t} + \left(\frac{1}{c^2}\right)\frac{\partial^2 z}{\partial t^2} = 0 \qquad (16)$$

By considering the inertia end condition, gives:

$$\left[\frac{\partial}{\partial x}\left(\frac{\partial^3 z}{\partial x^3}.\frac{\partial z}{\partial x}\right)\right]_{x=0} = \frac{a_s}{(1+C_a)}\left(\frac{\sigma^2}{c^2}\right)\cos(\sigma t) \qquad (17)$$

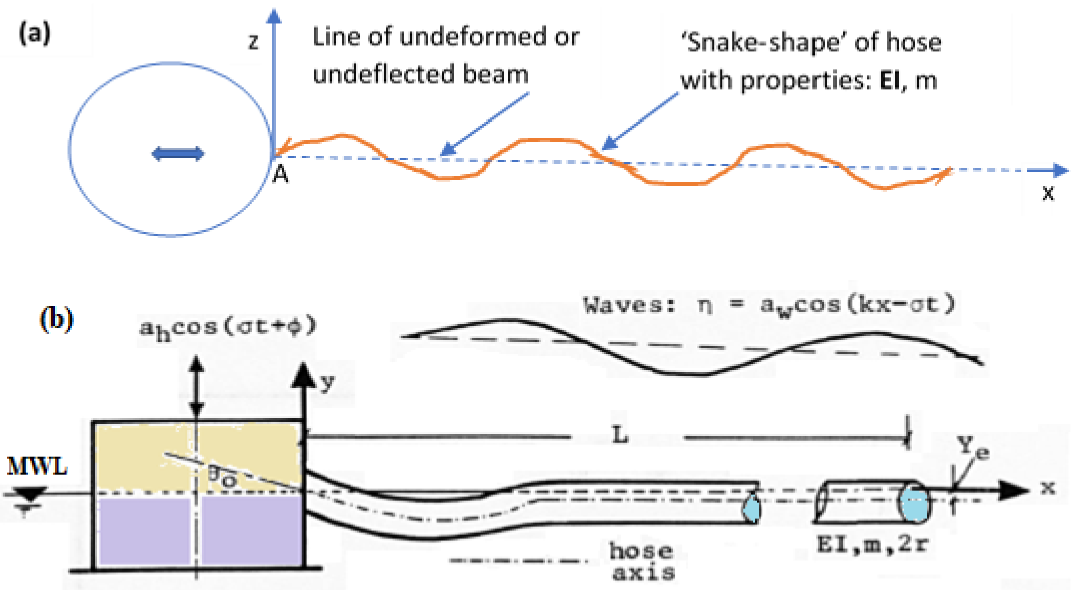

Figure 20 Definition sketch of the floating hose showing (a) the 'snaking' hose model, and (b) the vertical displacement and bending model

Taking the illustration of the snaking model in Figure 20, the solution without damping can be considered by taking V =*z(x,t)* + *iy(x,t)*; by assuming that the Euler beam equation without damping is represented by V as K approaches 0 (Bree J. et al. (1987)), thus gives;

$$\frac{\partial^4 V}{\partial x^4} + \left(\frac{1}{c^2}\right)\frac{\partial^2 V}{\partial t^2} = 0 \qquad (18)$$

And when the inertial end condition is satisfied by *z(x,t)*, it gives same Equation (16), thus:

$$\left[\frac{\partial}{\partial x}\left(\frac{\partial^3 z}{\partial x^3}.\frac{\partial z}{\partial x}\right)\right]_{x=0} = \frac{a_s}{1+C_a}\left(\frac{\sigma^2}{c^2}\right)\cos\sigma t \qquad (19)$$

Consider the solution in the form $V = Ae^{-i\omega t}$ when Equation (17) requires values of k=+ $k = \pm\frac{\sqrt{\omega}}{c}, \pm\frac{i\sqrt{\omega}}{c}$. Thus, Equation (17) presents a new solution for the waves in the floating buoy system, where the constants considered are A,B,C and D, as expressed:

$$V = Ae^{i\left[\left(\frac{\omega}{c}\right)^{\frac{1}{2}}x-\omega t\right]} + Be^{-i\left[\left(\frac{\omega}{c}\right)^{\frac{1}{2}}x-\omega t\right]} + Ce^{-\left[\left(\frac{\omega}{c}\right)^{\frac{1}{2}}x-\omega t\right]e^{-i\omega t}} + De^{\left[\left(\frac{\omega}{c}\right)^{\frac{1}{2}}x\right]e^{-i\omega t}} \qquad (20)$$

The terms of B and D can tend to zero in this mathematical expression based on physical grounds, whereby B=D=0, as they negative the terms for the waves in terms in A and C, thus:

$$V = Ae^{i\left[\left(\frac{\omega}{c}\right)^{\frac{1}{2}}x-\omega t\right]} + Ce^{-\left[\left(\frac{\omega}{c}\right)^{\frac{1}{2}}x-\omega t\right]e^{-i\omega t}} \qquad (21)$$

Where the first term of the RHS of Equation (21) is the travelling wave propagating away via the floating buoy while the standing wave is represented by the second term, which exponentially gets lower as x decreases.
By considering the inertial end condition, thus obtains:

$$C = 0;\ \omega = \frac{\sigma}{2};\ A = 2^{\frac{5}{4}}\left(\frac{a_s}{1+C_a}\right)^{\frac{1}{2}}\left(\frac{c}{\sigma}\right)^{\frac{1}{4}}e^{-i\frac{\pi}{4}} \qquad (22)$$

Applying Equation (22) into Equation (21), then obtains:

$$V = 2^{\frac{5}{4}}\left(\frac{a_s}{1+C_a}\right)^{\frac{1}{2}}\left(\frac{c}{\sigma}\right)^{\frac{1}{4}}e^{i\left[\left(\frac{\omega}{c}\right)^{\frac{1}{2}}x-\omega t\right]\frac{\pi}{4}} \qquad (23)$$

$$V = 2^{\frac{5}{4}}\left(\frac{a_s}{1+C_a}\right)^{\frac{1}{2}}\left(\frac{c}{\sigma}\right)^{\frac{1}{4}}e^{i\left[\left(\frac{\sigma}{2c}\right)^{\frac{1}{2}}x-\frac{\sigma}{2}t-\frac{\pi}{4}\right]} \qquad (24)$$

An accurate depiction for the motion of hose-string without damping can be represented as Equation (24), with consideration of the uniqueness of the equation, by taking the real part, thus:

$$z(x,t) = 2^{\frac{5}{4}}\left(\frac{a_s}{1+C_a}\right)^{\frac{1}{2}}\left(\frac{c}{\sigma}\right)^{\frac{1}{4}}\cos\left[\left(\frac{\sigma}{2c}\right)^{\frac{1}{2}}x - \frac{\sigma}{2}t - \frac{\pi}{4}\right] \qquad (25)$$

Although, while the hose -string approaches a narrow end towards x=0, when x>x_0, then x_0>2a_s. In the other hand, the solution with damping is considered by taking V =*z(x,t)* + *iy(x,t)*; by assuming that the Euler beam equation with damping is represented by V as K approaches 0 at inertial end conditions (Bree J. et al. 1987), thus gives;

$$\frac{\partial^4 V}{\partial x^4} + K\frac{\partial V}{\partial t} + \left(\frac{1}{c^2}\right)\frac{\partial^2 V}{\partial t^2} = 0 \qquad (26)$$

Consider the solution in the form $V = Ae^{-i\omega t}$ in Equation (26), presents the solution of the following form in Equation (27), where all the constants are depicted by A, B, C and D, while the values of $\alpha, \beta, H\ and\ \varphi$ are given by Bree J. et al. (1987);

$$V = Ae^{-\beta x}e^{i(\alpha x-\omega t)} + Be^{\beta x}e^{i(-\alpha x-\omega t)} + Ce^{-\alpha x}e^{i(-\beta x-\omega t)} + De^{\alpha x}e^{i(\beta x-\omega t)} \qquad (27)$$

4.4 Hydrodynamic Hose Load

Considering the CALM Buoy submarine hoses in Chinese-lantern configurations for SPM in Figures 14-16, the hose motion is subject to bending and environmental forces (Amaechi et al. 2019a, 2019b, OCIMF 2009). As depicted in Figures 21(a-d) and 22(a-d), the floats on the hoses influence the buoyancy and the configuration of the submarine hoses. Figures 22(a-b) shows that the hoses move relative to waves at different times while Figure 22(c-d) shows the parametric profiles, as it depicts that the maximum profile is highest for both the effective tension and curvature, followed by the mean and the least is the minimum profile. The parameters considered in hose design can be seen in hose studies. These parameters include the bending moment, curvature and effective tension distributions of the submarine hose-strings. In the model by Amaechi et al. (2019a), the hose profile was investigated for the effect of hydrodynamic loads on the submarine hose behaviour of hoses under different flow angles. By altering the flow angle, the results of the flow angle and hose hydrodynamic loads on the structural response of the hose were investigated. The influence of increased flexural stiffness at both top connections and bottom touch down sites (TDS) was studied, as were the patterns of bending and tension along hose arc lengths.

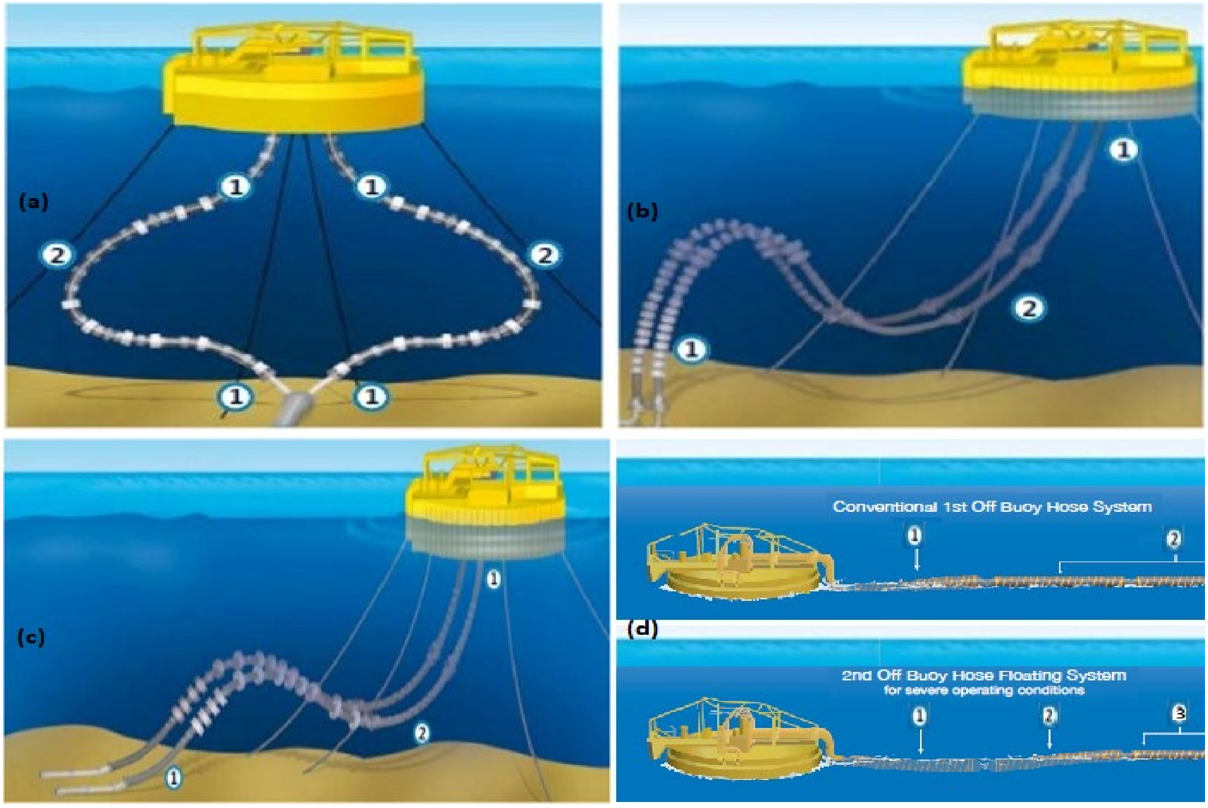

Figure 21 Marine hoses on (a) Chinese-lantern, (b) Steep-S, (c) Lazy-S, and (d) Off buoy hose configurations

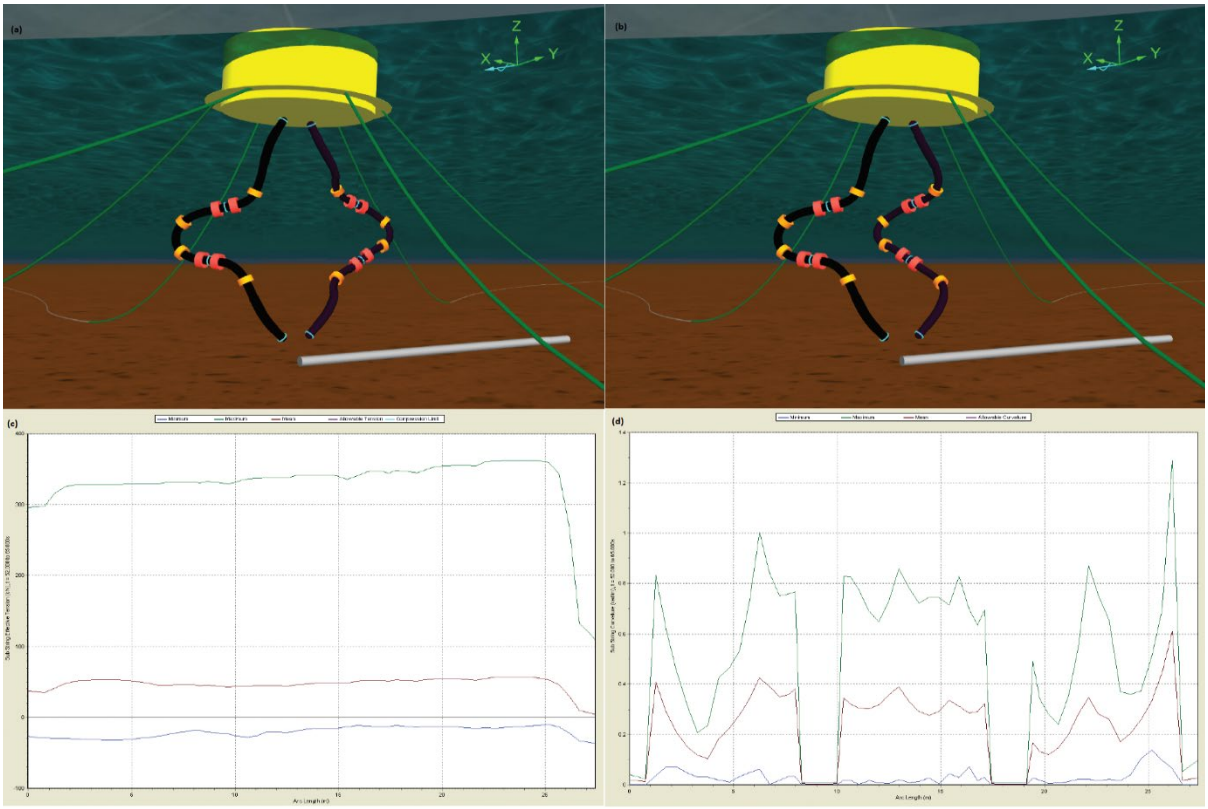

Figure 22 Marine hose model in Orcaflex configured as (a-b) Chinese-lantern, with its (c) tension and (d) curvature curves.

4.5 Hose Contact Pressure

Contact load is pertinent in bonded flexible risers and offshore hoses. Based on the component analysis, four key parameters are considered, namely the hose reinforcement, the end fitting and the contact and Metal Composite Interface (MCI). In the study by Cho and Song (2007), the contact pressure effect on a hose with three (3) layers was investigated, and they found that the pressure increased after relaxation. It was also highest at the innermost layer of the hose, as observed on the contact in Figure 23(a-c). The stress relaxation was computed starting from the point of release of Jaw 2 to 7.0×10^3 s. The study results showed that the peak stress in the inner rubber layer decreases suddenly and greatly just after the release of Jaw 2, implying that the stress relaxation was maximum within the inner rubber layer of the hose. In Figure 23(d), it can also be seen that when hose is pressurized, the bending moment profile is highest in *Hose1*, next to *Hose2*, while the empty hoses are the least which shows the effect of contact pressure holding the layers together to be able to hold the hydrostatic pressure in place. As such, the effect of contact is a very important parameter in the bonding of bonded marine hoses. The pressurised hose's increased bending stiffness is due to the cross-section ovalization caused by the bending moment. As a result, the inertial moment and bending stiffness are lower in the ovalized cross-section. According to Polenta et al. (2015), this increase in bending stiffness happens because the pressure acting on the inner surface tends to keep the cross-section round. As demonstrated in Figure 23(d), the model of Tonatto et al. (2018) can likewise capture the increase in stiffness owing to internal pressure. Due to the ovalization of the hose, there was no non-linear behaviour. This behaviour is due to the way the curvature in the bending test was assessed.

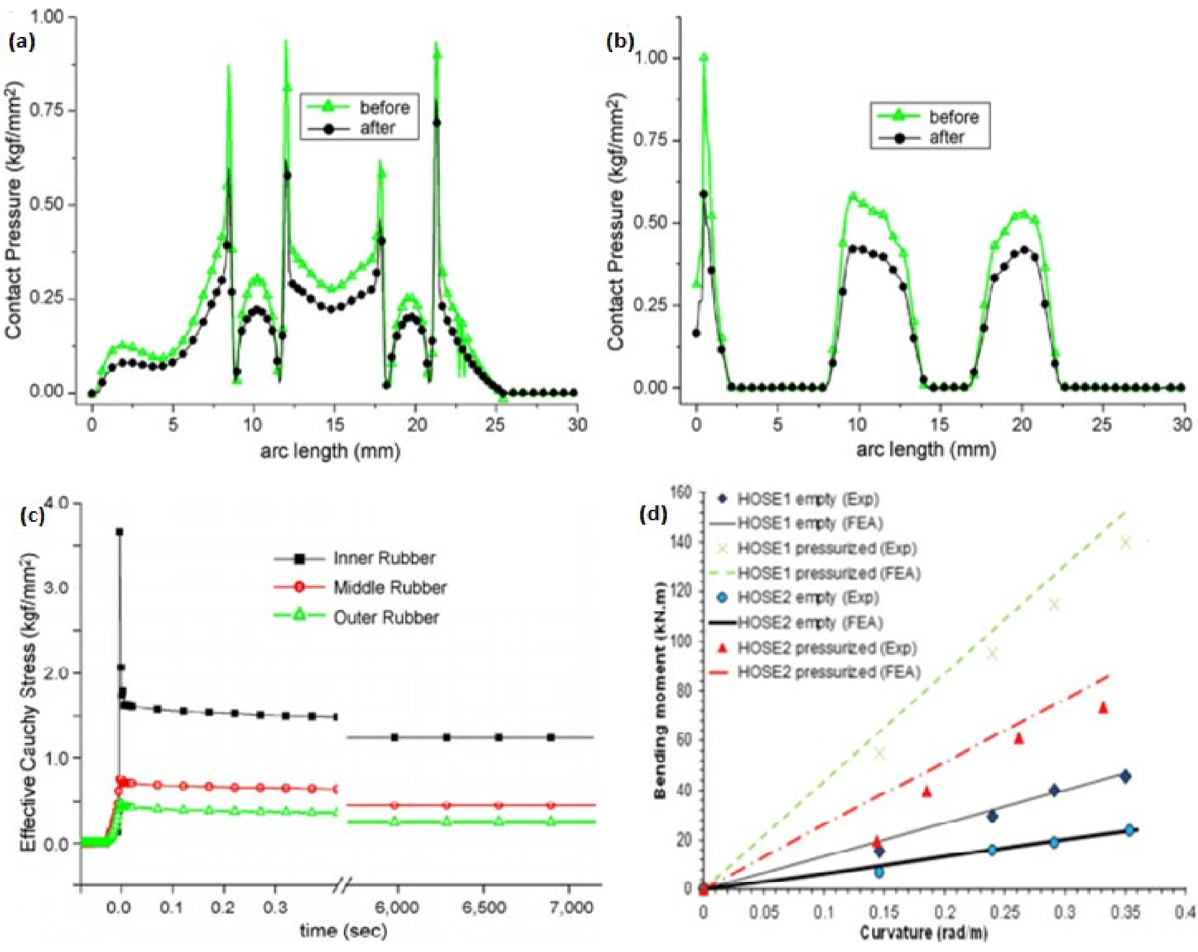

Figure 23 Effect of contact pressure on reinforced hoses, showing (a)stress relaxation history, (b) contact pressure at the bottom surface and (c) contact pressure at the top surface (Courtesy: [a-c] Cho and Song, 2007 & [d] Tonatto et al. 2018)

4.6 Hose Pressure & Flow Velocity

Industry hose pressures are designed with respect to the flow rate, as given in Figure 24(a-c), shows that pressure loss increases as flow rate increase over time. For each nominal hose diameter, the graphs below show the relationship between pressure loss and flow rate. Under some conditions, the pressure loss and flow rate can be estimated using the Darcy – Weisbach equation and Mise's experiment. In this case, the parameters include a 100m hose-line lengthwise, the fluid's specific gravity is 0.85, the rheological properties for kinematic viscosity as 6.0 x 10^{-6} and the result Mise's experiment was 0.3 x 10^{-6}. It can be observed that the least hose diameter of 150mm has the maximum pressure loss of 15bar while the highest hose diameter of 600mm has the least pressure loss of 2.5bar. GMPHOM OCIMF (2009) recommends a maximum flow velocity of 21 m/sec (70 ft/sec). The plot in Figure 24(d) depicts the relationship between flow rate and flow velocity for each nominal hose diameter. Thus, it can be concluded that the pressure loss is a function of the hose diameter and flow rate.

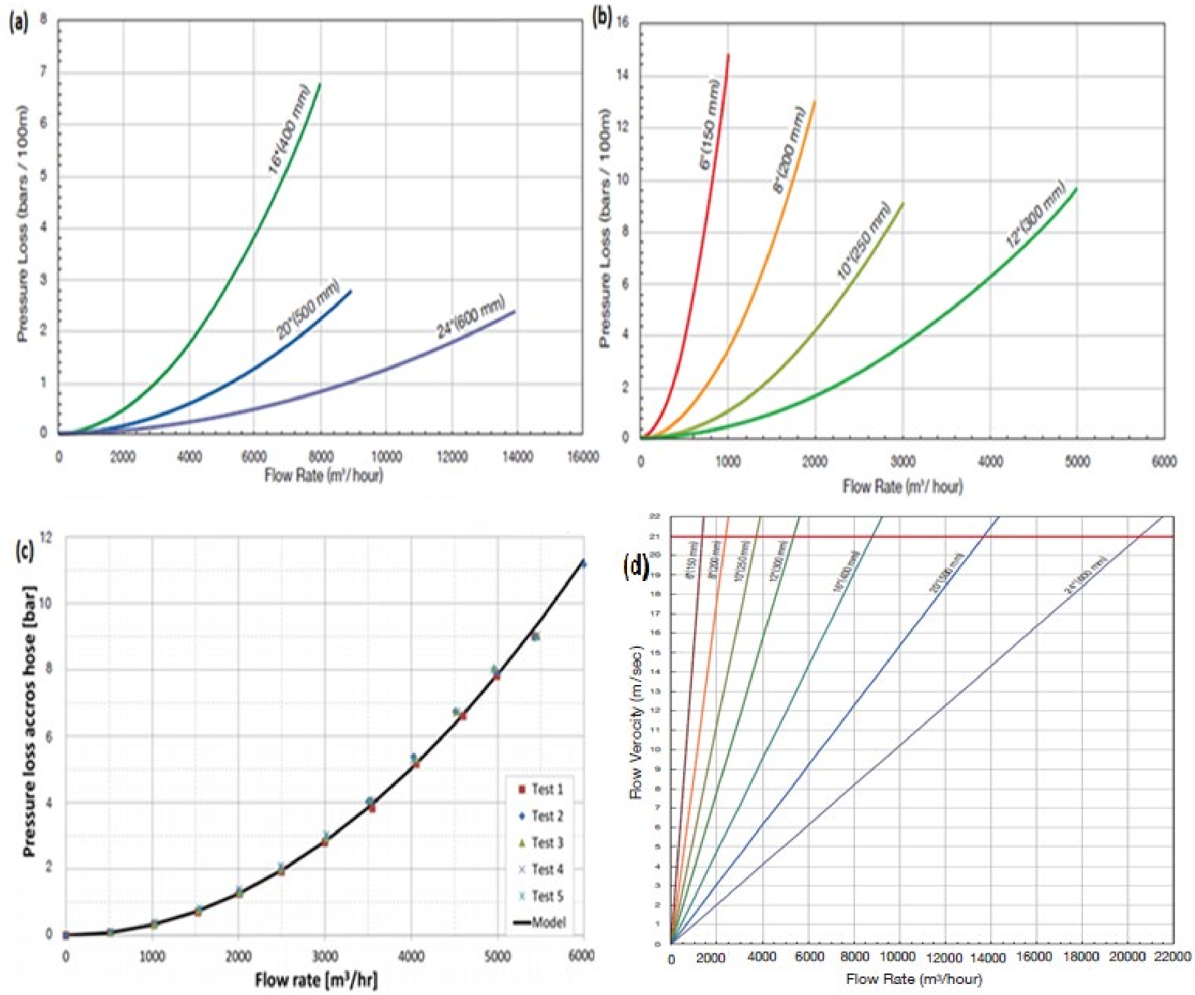

Figure 24 Pressure against flow rate of offshore hoses, showing (a-c) pressure loss against flow rate, for different sizes of hoses, and (d) flow velocity against flow rate (Courtesy: Yokohama & Trelleborg)

4.7 Failure modes of Bonded marine Hoses

Due to the HPHT requirement of marine hoses and the industry specifications such as the GMPHOM (OCIMF 2009) standard, it is crucial to inspect hoses regularly from manufacturing to certification, storage, transportation, installation, to operation stages. Bonded flexible risers and offshore hoses have also been identified to have failure issues such as corrosion on rubberised offshore hoses (Løtveit S. A. 2009, 2018, PSA 2018, PSA 2013). As seen on Figure 25 and Table 10, there are different issues that may lead to the issues of failure on offshore hoses. However, failures identified on rubberised hoses can be due to operation loads from flange corrosion, liner leakages, cuts from propeller, as summarised in Figure 25. Due to the multi-layers of offshore hoses and bonded flexible risers, the damages caused can be complex, and not always repairable. As such, there is the need to investigate these hoses against these failures, using more advanced modelling methods.

Figure 25 Collage of different hose failure modes, showing (a) pressure test with leaking liner, (b) floating hose after a propeller cut, (c) excess cover damage down to breaker fabric, (d) corrosion and heavy wear of the hose flange that had a service life of 14 years, (e) hose damage from abrasion cut on cover (f) crushed 16 inches submarine hoses after excessive load landed on it, (Courtesy: PSI, 4Subsea, Continental Dunlop & Trelleborg)

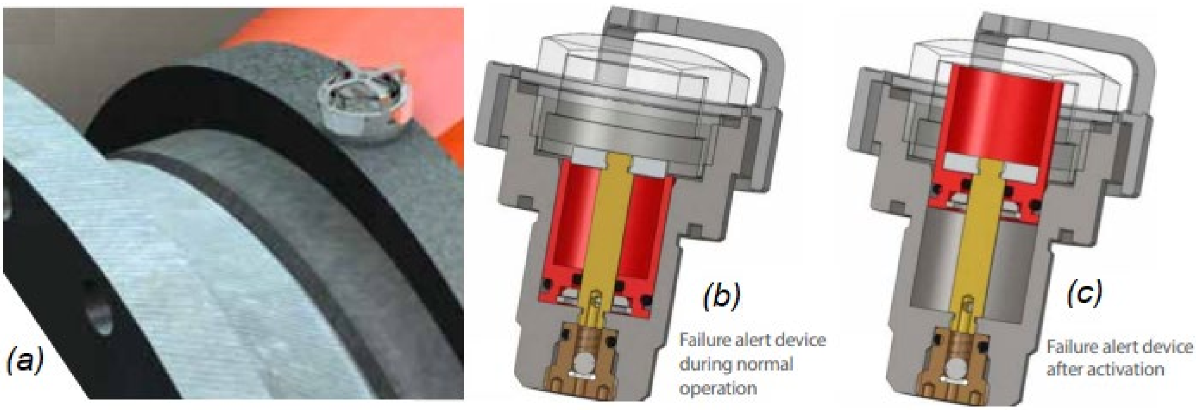

Figure 26 A Hose monitoring system called failure alert device (FAD) on (a) Manuli's Dual Anti-pollution Safety Hose (DASH), (b) FAD during normal operation, and (c) FAD after activation (Courtesy of: Manuli & Offspring International)

Recent advances include the incorpaoration of sensors and Offshore Monitoring Systems (OMS) on hoses and CALM buoys to have real-time reporting on failure propagation, failure inception, and failure modes on these hose systems. According to OIL (2020), most leak detection systems just keep an eye on the primary carcass, but the challenge is on the effect of failure from the secondary carcass. Figure 26 shows a failure alert device (FAD) on Manuli's Dual Anti-pollution Safety Hose (DASH), which monitors the integrity of both the primary and secondary hose. A stainless-steel base is covered with a clear plastic lens and protected by a stainless-steel cage in the mechanical FAD. The pressure between the primary and secondary sections of the hose makes the system work. Whenever a leak from the original carcass develops, the secondary carcass contains it, increasing the pressure. When the fluid reaches the FAD base, it activates, raising the coloured piston that can be seen from afar.

Table 10 Failure modes of offshore hoses and unbonded flexible risers

Failure Mode	Description	Observations & Recommendations
Hose line failure due to Nipple or End-fitting corrosion	Hoses can have some failures when the nipple or end fitting of the hose starts to corrode. In that case, the service life will be shortened. This will weaken the adhesion and contact forces between the hoses and these bonded steel.	Different industry hose manuals specify that routine checks be carried out. Also, the hose-string be designed according to OCIMF GMPHOM and API 17K standards.
Elastomeric-steel bonds and fabric-reinforcement-cord bonds having failure in the bonding	The elastomeric layers must be properly bonded to both the end connection and the reinforcing cable in bonded pipes. End terminations have been blown off the hose due to bonding failure during pressure testing. Rejection has also been induced by leakage and perspiration. Dissections are usually the only way to detect bonding breakdown between the armour or reinforcement layers.	GMPHOM OCIMF (2009) and API 17K specifications include: - Specifications for each length of hose - Handling and documentation of materials - Bonding agents and surface preparation
Hose test failures	Only hoses with an elastomeric liners are subject to pipe rejection owing to vacuum testing. For high-pressure gas applications, kerosene tests and cyclic gas decompression tests have resulted in hose rejection owing to de-bonding and/or scorching.	Each hose length is subjected to a hydrostatic pressure test, as well as adhesion testing for each batch of material and every tenth hose length. Each pipe length is vacuum tested; For each hose length, the purchaser specifies a kerosene test.
Operation damages	It is important to carry out routine checks on the hoses. There could be wear and tear on the hose due to contact with other hoses as when reeled, or impact during transfer. This can cause abrasion damages.	Different marine brochures by industry manufacturers also recommend these checks, such as by Dunlop Continental, Yokohama Seaflex, Trelleborg, EMSTEC, etc.
Surface damages	It is important to do physical inspection of the hoses. Occasionally, hose lengths can be rejected from visual inspection due to surface damage found on the cover.	GMPHOM OCIMF (2009) and API 17K specifications on surface damage: - Generally, liner repair is not permitted. - Minor repair of outer cover is permitted with an approved procedure
Liner leak	Pressure will build up in the pipe wall as a result of a leaky liner. Such flaws are usually detected by pressure resistance test.	Burst (internal pressure) test is usually recommended.
Damages due to improper handling or storage	Storage, maintenance, and handling advice are included with every bonded hoses. Failure due to inappropriate handling and storage does not seem to be a problem if these guidelines are followed. Incorrect handling, on the other side, has culminated in crushing and kinking failures.	The hose must be stored and managed according to the manufacturer's guidelines, as stated in the specifications.
Connection point to Valves leakages	Some failure have been reported largely that occur due to failure of valves or connection points of the valves to the marine hoses. As such, it is advised that the operators and manufacturers do enough checks and tests on this before delivery, and deployment on the field.	Both marine hose operators and the hose manufacturers conduct adequate checks and tests on this before delivery, and deployment on the oil-field or (un)loading terminal. It is recommended that this checks should include service usage with hose-valve connections.

5.0 Conclusion

A detailed review on the design and mechanics of bonded marine hoses for CALM buoys has been conducted. This is necessary, considering the large amount of applications currently existing that use CALM buoys, marine hoses and other single point (SPM) moorings, as represented in Appendix A, Table 11. It shows 40 current offloading hose systems, CALM buoys, and industry operators, but the list is not limited to these 40 projects. The state-of-the-art on hose structures application, recent developments, advanced applications of hose structures are also presented. This study shows that environmental loads like wind and the ocean currents influence hose performance. Also, the hose model and environmental conditions like the peak periods, influence the hose behaviour. With the application of bonded flexible risers and bonded flexible pipes, the transfer of oil and gas products in FLNG (Floating LNG production unit) has been possible, despite being relatively new. The FLNG applications use the long and large bore seawater intake hoses and the LNG offloading hoses, while others use specialist marine hoses. As discussed, the development of marine hoses in the industry has accelerated in recent decades. This trend is due to the utilisation of marine hoses on various platform and mooring designs, enabling fluid products' offloading. Currently, marine hose users have not presented many hose failures; however, this area has a limited experience base (Svein Are Løtveit 2009, 2018, PSA 2018, 2013). There are some in-service failures on crude offloading hoses reported. However, the application is in high demand. More mathematical theories, formulations, and solutions have also been proffered to solve these issues in this review.

The main highlights of this review are as follows:

- Design criteria, developmental trends, tests, standards, and mechanics of bonded marine hoses.
- Numerical modelling review, and marine hoses assessment on CALM buoy hose systems.
- Theoretical models on load responses of marine hoses, effect of waves and hydrodynamics
- Marine industry application of hose configurations, hose models and material models.
- Overview on failure modes of bonded marine hoses and their merits for marine applications.

During marine hose qualification, all the checks have to be carried out, and necessary test conducted. Also, quality checks, safety checks, qualification and service assurance are done on each in-service offloading hose projects based on the industry guidelines. Despite the extensive qualification programs on marine hoses, there are still recent reports of new in-service failure modes not identified in the qualification. As such, more investigation - both numerically using FEA and CFD should be carried out. Failure of offshore hoses can lead to oil spills, such as the oil spill in 2010. Oil spillage can increase the CAPEX (capital expenditure), increase maintenance cost and increase the production down time. It is always advised also to have consultants check these hose designs from manufacturing to installation stages. There are still some challenges on numerical investigations on marine hoses that were lacking from the review study. These include researches of offshore hoses on nonlinear seabeds, comparative study of configuration of submarine and floating hose string with Orcaflex (Ocina 2014, 2019, 2020, 2021) and Flexcom and other analytical dedicated software for hoses, study of pressure losses and determination of optimal diameter on offshore hoses, study on fatigue estimation of offshore hoses on Orcaflex or similar platforms, surge pressure analysis with FEA on ANSYS (ANSYS 2016a, 2016b) and ABAQUS or similar FEM codes, study of new configuration on identification of hoses, analysis of optimal length of strings and the identification and supply of proper hose ancillaries, hose replacement dynamics, hose abandonment dynamics, and the effect of hose ancillaries like HEV on reeling hoses, lastly the impact of crushing load on reeling hoses. In conclusion, the hose behaviour when attached to the host FOS is relative to the operational activity. As such, some designs done are analytical estimations rather than a full design on the offshore hoses. However, having better design methods implies that these hoses will have increased service life during operation. This review was effective in developing a theoretical solution to explain the mechanical behaviour of the reinforcing layers for loading and offloading hoses. It presents developments from industrial hose manufacturers, as such, has excellent industrial relevance. This review advocates for more synergies between industry and academia. It also serves as the guidance for standard elaboration, future study on the useful art of hoses and for funding applications. It aims towards the growth of hose technology in ocean engineering and related fields. It will also ensure that marine hoses are designed efficiently with a longer lifespan.

Conflict of Interest

The authors declare no conflict of interest in this review.

Data availability statement

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

Authorship CRediT Contribution Statement

Conceptualization, C.V., F.W. and J.Y.; methodology, C.V., C.C., H.O.B., J.Y., and F.W.; software, C.V., C.C., H.O.B., and J.Y.; validation, C.V., C.C., H.O.B., F.W., and J.Y.; formal analysis, C.V., C.C., H.O.B., F.W. and J.Y.; investigation, C.V., C.C., H.O.B., and J.Y.; resources, C.V. and J.Y.; data curation, C.V., C.C., H.O.B., and J.Y.; writing—original draft preparation, C.V.; writing—review and editing, C.V, C.C., H.O.B., F.W., and J.Y.; visualization, C.V, C.C., H.O.B., and J.Y.; supervision, C.V., J.Y., and F.W; project administration, C.V., J.Y. and F.W.; funding acquisition, C.V., J.Y., and F.W.

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Appendix

Table 11 Existing offloading hose systems and industry operators

S/N	Name	Water Depth	Location	Year Installed	Tanker Range (DWT)	Buoy Dimension	Hoses & the Configuration	Operator
1	Dangote CALM Buoys SPM-C1, SPM-C2,	36m, 40m	Port of Lekki, Nigeria	2017	320,000	Ø=12.5m h=5.3m	Floating Hose = 60.96cm, Submarine Hose=60.96cm; Double carcass;	Dangote Petroleum
2	Dangote CALM Buoys SPM-P1, SPM-P2 & SPM-P3	22m, 24m & 22m	Port of Lekki, Nigeria	2017	160,000	Ø=11.5m h=5.0m	Floating Hose = 60.96cm, Submarine Hose=60.96cm; Double carcass;	Dangote Petroleum
3	Jazan CALM Buoy	27.4m	Jazan, Saudi Arabia	2017	320,000	Ø=12.5m h=5.3m	Floating Hose = 60.96cm, 50.8cm; Submarine Hose=60.96cm; Chinese Lantern	Saudi Arabian Oil Company
4	SEPOC RAS ISSA CALM Buoy	32.5m	Ras Issa Penninsula, Red Sea, Yemen	2017	300,000	Ø=12.5m h=5.3m	Floating Hose = 50.8cm; Submarine Hose=50.8cm; Chinese Lantern	SAFER Expl. & Produc. Oper. Company
5	Ngih Son CALM Buoy	27m	Ngih Son, Vietnam	2015	320,000	NA	NA	JGC Corporation
6	PNG – Kumul CALM Buoy	35m	Gulf of Papua, New Guinea	2012	120,000	Ø=12.5m h=5.3m	Floating Hose = 40.64cm, 30.48cm; Submarine Hose=30.48cm;	Oil Search Limited
7	PEMEX Tuxpan CALM Buoy	18m	Tuxpan Terminal, Mexico	2013	60,000	Ø=11m h=4.5m	Floating Hose = 40.64cm, Submarine Hose= 40.64cm, Chinese Lantern	PEMEX Refinacion
8	PEMEX Rosarito CALM Buoy	23m	Rosarito Terminal, Baja California, Mexico	2013	60,000	Ø=11m h=4.5m	Floating Hose = 40.64cm, Submarine Hose= 40.64cm, Chinese Lantern	PEMEX Refinacion
9	PEMEX Salina Cruz CALM	23m	Salina Cruz Terminal, Mexico	2013	60,000	Ø=11m h=4.5m	Floating Hose = 40.64cm, 25.4cm Submarine Hose= 40.64cm, 25.4cm; & Chinese Lantern	PEMEX Refinacion
10	Barber's Point (Tesoro) CALM	31m	Barber's Point, Hawaii, USA	2012	150,000	Ø=11m h=4.5m	Floating Hose = 40.64cm, 30.48cm Submarine Hose= 40.64cm, 30.48cm; & Chinese Lantern	Tesoro Hawaiian Corporation
11	Malampaya CALM buoy	75m	Palawan Island, offshore South China Sea, Philippines	2001	40,000 – 110,000	Ø=12.5m h=5.3m	Floating Hose = 40.64cm, Submarine Hose=30.48cm; Lazy-S	Shell
12	Nagarjuna CALM	31m	Nagarjuna, India	2012	300,000	Ø=11.0m h=5.8m	Floating Hose = 60.96cm, Submarine Hose=60.96cm;	Nagarjuna Oil Corporation Limited-NOCL

13	NuStar CALM buoy	64m	N.V. in Tumble Down Dick Bay, St. Eustatius, Netherland Antilles	2008	520,000	Ø=12.5m h=5.8m	Floating Hose = 60.96cm, 50.80cm; Submarine Hose=60.96cm, 50.8cm; & Lazy-S	NuStar Energy
14	Statia Terminal CALM Buoy	64m	St. Eustatius, Netherland Antilles	1994		Ø=12.5m h=5.8m	Floating Hose = 60.96cm, 50.80cm; Submarine Hose=60.96cm, 50.8cm; & Lazy-S	NuStar Energy
15	St. Eustatius CALM Buoy	65m	St. Eustatius, Netherland Antilles	1993	520,000	Ø=12.5m h=5.8m	Floating Hose = 60.96cm, 50.80cm; Submarine Hose=60.96cm, 50.8cm; & Lazy-S	Chicago Bridge & Iron (CBI) / Statia Terminals
16	EIL/Bharat CALM Buoy	35m	Bina Refinery Field (BORL 1), Jamnagar, India	2009	320,000	Ø=12.5m h=5.3m	Floating Hose = 60.96cm	EIL/Bharat Oman Refinery
17	Pertamina 150 CALM Buoy #2	24.6m	TTU, Tuban Field, Indonesia	2008	150,000	Ø=11.0m h=5.0m	Floating Hose = 60.96cm, Submarine Hose= 50.8cm;	Inti Karya Persada Tehnik (IKPT)
18	Pertamina 035 CALM Buoy #1	18.6m	TTU, Tuban Field, Indonesia	2008	150,000	Ø=11.0m h=5.0m	Floating Hose = 40.64cm, Submarine Hose= 40.64cm;	Inti Karya Persada Tehnik (IKPT)
19	Pagerungan CALM Buoy	65m	Kangean Islands, Indonesia	1993	125,000	Ø=11.0m h=5.0m	Floating Hose = 30.48cm; Submarine Hose= 30.48cm & Lazy-S	ARCO Bali North Inc.
20	Termap S.A. CALM buoys #1 & #2	37m, 42.3m	Caleta Cordova & Caleta Olivia Fields, Argentina	2009	160,000	Ø=12.5m h=5.3m	Floating Hose = 50.8cm, Submarine Hose= 50.8cm;	Termap S.A.
23	CFE CALM Buoy	16m	Tuxpan, Mexico	1994	45,000	Ø=9.5m h=3.0m	Floating Hose = 40.64cm, Submarine Hose= 40.64cm; Chinese Lantern	Comision Federal de Electricidad (CFE)
24	Butinge CALM Buoys #1 & #2	20m	Butinge Terminal in Baltic Sea, Lithuania	1998 & 2006	35,000 – 80,000	Ø=12.5m h=5.3m	Floating Hose = 40.64cm, Submarine Hose= 40.64cm; Chinese Lantern	Butinge Nafta
25	Mina al Ahmadi CALM Buoys #1 & #2	31m	Mina al Ahmadi, Kuwait	1995 & 2008	456,000	Ø=12.5m h=5.3m	Floating Hose = 60.96cm, 50.80cm; Submarine Hose=60.96cm, 50.80cm; & Chinese Lantern	HHI /NPCC / Kuwait Oil Company (KOC)
26	Sonatrach Arzew #1 & #2 CALM Buoys	62m, 53m	Algeria-North Africa	2005	NA	Ø=12.5m h=5.3m	Floating Hose = 60.96cm, 40.64cm; Submarine Hose=60.96cm, 40.64cm	Sonatrach TRC
27	Sonatrach Skikda #1 & #2 CALM Buoys	61m, 81m	Algeria-North Africa	2005	320,000	Ø=12.5m h=5.3m	Floating Hose = 60.96cm, 40.64cm; Submarine Hose=60.96cm, 40.64cm	Sonatrach TRC
28	Sonatrach Bejaia CALM Buoy	41m	Algeria-North Africa	2005	80,000	Ø=12.5m h=5.3m	Floating Hose = 60.96cm, 40.64cm; Submarine Hose=60.96cm, 40.64cm	Sonatrach TRC
29	Vehop CALM Buoy	25m	Jose Terminal, Venzuela	1997	96,920	Ø=12.5m h=5.3m	Floating Hose = 50.8cm;	Petrozuata

							Submarine Hose= 50.8cm; Chinese Lantern	
30	Jebel Dhanna CALM Buoy #1 & #2	21m & 23m	Jebel Dhanna, UAE	1995 & 1999	450,000	Ø=11.0m h=4.5m	Floating Hose = 50.8cm; Submarine Hose= 50.8cm; Chinese Lantern	Abu Dhabi Company (ADCO)
31	OCP #1 (Charlie) CALM Buoy	31m	Balao terminal, Ecuador	2003	130,000	Ø=12.5m h=5.3m	Floating Hose = 60.96cm; Submarine Hose= 60.96cm & Chinese Lantern	OCP/ Techint
32	OCP #2 (Papa) CALM Buoy	41m	Balao terminal, Ecuador	2003	250,000	Ø=12.5m h=5.3m	Floating Hose = 60.96cm; Submarine Hose= 60.96cm & Lazy-S	OCP/ Techint
33	RAVVA CALM Buoy	25m	RAVVA Field, Andhra Pradesh, India	1998	120,000	Ø=12.5m h=5.3m	Floating Hose = 50.8cm, Submarine Hose= 50.8cm, 40.64cm;	Cairn Energy India Pty. Ltd.
34	Terrunganu CALM Buoys #1 & #2	20m	Kerteh, West Malaysia	1982 & 1999	85,000	Ø=11.5m h=3.3m	Floating Hose = 50.8cm, Submarine Hose= 40.64cm; Chinese Lantern	Petronas Carigali
35	CPC Ta Lin Pu CALM Buoys #3 & #4	36m & 26m	Kaohsiung, Taiwan	1991 & 1992	300,000 & 100,000	Ø=12.5m h=4.8m	Floating Hose = 50.8cm, Submarine Hose= 50.8cm, Chinese Lantern	Chinese Petroleum Corp. (CPC)
36	Hazira CALM Buoy	29.4m	Surat, India	1990	50,000	Ø=9.5m h=3.8m	Floating Hose = 40.64cm, 25.4m; Submarine Hose= 40.64cm, 25.4m; Chinese Lantern	Oil & Natural Gas Commission (ONGC)
37	HIRI CALM Buoy	31m	Oahu Island, Hawaii, USA	1987	150,000	Ø=11.5m h=4.0m	Floating Hose = 40.64cm, 30.48m; Submarine Hose= 40.64cm, 50.8m; Chinese Lantern	Hawaiian Independent Refinery Inc. (HIRI)
38	Palenque CALM Buoy	25m	Palenque, Rafidonsa Refinery, Dominican Republic	1985	100,000	Ø=10.5m h=4.0m	Floating Hose = 40.64cm, Submarine Hose= 40.64cm; Chinese Lantern	Shell
39	ADMA/ OPCO SARB CALM Buoy	28m	Satah Al-Razboot (SARB), Zirku, UAE	2015	320,000	Ø=12.5m h=4.8m	Floating Hose = 50.8cm, Submarine Hose= 50.8cm, Chinese Lantern	ADMA/ OPCO
40	ADMA/ OPCO CALM Buoy #1 & #2	28m & 26m	Das Island, UAE	1991 & 2005	500,000 & 360,000	Ø=12.5m h=4.8m	Floating Hose = 50.8cm, Submarine Hose= 50.8cm, Chinese Lantern	ADMA/ OPCO