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REVIEW ARTICLE

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# A literature review on the technologies of bonded hoses for marine applications

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**ABSTRACT**

Marine bonded hoses are conduit-tubular structures used for loading, discharging, transferring and transporting fluid products like oil, gas, and water. These marine conduits are applied in the offshore industry by utilising novel marine materials and sustainable technologies. Based on sustainability, there are advances made as solutions for challenging environments. These challenges include scouring gases, deep water regions, changing sea water temperatures, platform loads and vessel motions. These environments also require sustainable materials like marine composites. This paper reviews historical timeline and patent development of hoses in the marine environment. It highlights key developments on marine hoses and their configurations. These configurations include FPSO-FSO with hose attachments in catenary configurations and CALM buoy-PLEM in Lazy-S configurations. The review also discusses the evolutions in the hose designs, potentials of the hoses, and recent state-of-the-art developments in the industry. Comprehensive discussions with necessary recommendations are made for fluid applications in the offshore industry.

**Abbreviations:** 3D: Three Dimensional; ABS: American Bureau of Shipping; API: American Petroleum Institution; BSI: British Standards Institution; BV: Bureau Veritas; CALM: Catenary Anchor Leg Mooring; CAPEX: Capital Expenditure; CFD: Computational Fluid Dynamics; CL: Chinese-lantern (hose configuration); COOL™: Cryogenic Offshore Offloading and Loading; DC: Dual Carcass or Double Carcass; DNVGL: Det Norkse Veritas & Germanischer Lloyd; DOM: Dunlop Oil & Marine; DOE: Design of Experiment; DP: Dynamic Position; D/t: Diameter/thickness; DWS: Dual Warning System; EN: Europäische Norm ('European Norm') Standards; FAT: factory acceptance test; FEA: Finite Element Analysis; FEM: Finite Element Modelling; FLNG: Floating Liquefied Natural Gas; FMECA: Failure Mode, Effects, and Criticality Analysis; FOS: Floating Offshore Structure; FPSO: Floating, Production, Storage and Offloading; FSO: Floating storage and offloading; FSP: Floating storage and processing; GMPHOM: Guide to Manufacturing and Purchasing Hoses for Offshore Moorings; HAZID: Hazard identification; HEV: Hose End Valve; ID: Inner Diameter; IMO: International Maritime Organisation; IMS: Integrated Monitoring Systems; IOFBS: Inflatable Offshore Fender Barrier Structures; ISO: International Standards Organisation; KGK: Kautschuk und Gummi Kunststoffe; 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; OIL: Offshpring International Limited; OLL: Offloading / Loading Lines; OOL: Offshore Offloading Lines; OPEX: Operational Expenditure; PLEM- Pipeline End Manifold; PLUTO- PipeLine Across The Ocean; SALM: Single Anchor Leg Mooring; SC: Single Carcass; SCR: Steel Catenary Risers; SLF: Stress Loading Factors; SON: Standards Organisation of Nigeria; SPM: Single Point Mooring; SRSH: Special Reinforced Submarine Hose; SS: Seaflex Super stream; STD: Standard Type; SURP: Subsea Umbilical Risers And Pipelines; SWIR: Sea-Water Intake Riser; TWS: Twist Warning System; UK: United Kingdom; US: United States

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Bonded marine hose; flexible marine riser; floating offshore structure (FOS); offshore platform; hose development; catenary anchor leg mooring (CALM) buoy

## 1. Introduction

The oil and gas sector requires new flexible methods, designs, and conduits that can be deployed to implement explorations at some well sites. This is conducted using more sustainable and energy efficient methods to reduce carbon emissions (Odijie et al. 2017a, 2017b; Wang et al. 2019; Zhang et al. 2019; Ali et al. 2020), as energy consumption globally is expected to rise by 28% before 2030 (IEA 2017; Doyle and Aggidis 2019). Thus, more sustainable approaches have also been considered in recent times by using marine composites in the development of marine bonded hoses, despite its size,

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service functionality, and application in the ocean. The ocean itself covers over 75% of the earth's surface and has the highest source of fossil energy resources, natural gas deposit and crude oil deposits which are been extracted, explored but not effectively harnessed. The exploration of crude oil involves a variety of floating offshore structures (FOS) (Chakrabarti 1994, 2001, 2002, 2005; Wilson 2003; Sarpkaya 2014; Odijie 2016). Figure 1 shows an ocean environment with different offshore platforms and applications of marine bonded hoses. However, hoses have some attributes like bending stiffnesses, vertical bending moments and axial forces (Pinkster and Remery 1975; Quash and Burgess 1979; Young et al. 1980; Tschoepe and Wolfe 1981; O'Donoghue 1987; O'Donoghue and Halliwell 1990; Chakrabarti 1994; Ryu et al. 2006; Antal et al. 2012). Despite the availability of various patents on marine hoses, marine risers, pipelines, there are still limited reports on full-scale developments on marine bonded hoses despite the progress that has been made in industry and its commercialisation.

One method of achieving sustainable fluid transfer is by the use of marine hoses in the offshore industry. By definition, marine bonded hoses are conduit-tubular structures used for loading, discharging, transferring, and transporting fluid products- oil, gas, and water. By rationalisation, it creates a new way of sustainable work delivery and enhances better investment in the supplier/manufacturer relationships. Sustainability creates a growing realisation that leads to engagement in long-term solutions on the issues of fluid transfer. These issues include flexible platform needs and easier configurations. Based on product development, the dichotomy that is conspicuous between academic research and industrial applications. However, it also creates some technical issues, slows down development and limits research outputs. Thus, the streamlined provisions of the industrial standards available -OCIMF GMPHOM (OCIMF 2009) and API 17 K (API 2017), have been helpful for design specifications and structural detailing. By classification, these hoses could be subsea hoses (or submarine hoses),


Figure 1. Offshore application of marine bonded hoses showing different offshore platforms and marine hoses (This figure is available in colour online).

Figure 2. The extreme size of dredging hoses compared to floating hoses (Courtesy: Antal et al. 2012; Adapted with permission of Germa Hornsby of Continental Dunlop Oil & Marine) (This figure is available in colour online).

**Table 1.** Historical timeline on the development of marine bonded hose technologies, with founding years of manufacturers.

| Year | Progress Made, Buoy / Hose Manufacturer & Joint Industry Project (JIP) | Reference |
|---|---|---|
| 1871 | Continental AG was founded as Continental-Caoutchouc und Gutta-Percha Compagnie | Continental (2014, 2021) |
| 1898 | Dunlop Rubber Company (formerly Pneumatic Tyre and Booth's Cycle Agency Ltd.) was established. In addition, GoodYear Tire & Rubber Company was founded | Dunlop (2015), GoodYear (2021), NationalArchives (2021) |
| 1905 | Trelleborgs Gummifabriks AB (the Rubber Factory Corporation of Trelleborg) founded | Trelleborg (2021, 2018) |
| 1917 | The Yokohama Rubber Co., Ltd. was established | Yokohama (2016) |
| 1920s | Continental merger started Continental Gummi-Werke AG | Continental (2021) |
| 1925 | Eddelbüttel + Schneider was founded to manufacture hoses and sleeves for dredging and mining. It is now part of Continental ContiTech Group. | DSMA (2019), Richardson (2004) |
| 1935 | Manuli Rubber Industries was established | ManuliRubber (2021) |
| 1949 | Shenyang Rubber Tube Factory was established | VHMarinTech (2021) |
| 1960 | Yokohama marketed its first marine hose in 1960. Since then, Yokohama has succeeded in making a number of technological breakthroughs in product development | Yokohama (2016) |
| 1962 | Float Sink hose system for SPM – Yokohama's helix free main line hose with air buoyancy. | Yokohama (2016) |
| 1964 | The first commercial maritime pipeline, based on marine power cable technology, was built between two Danish islands | Sparks (2018) |
| 1965 | Durham Rubber & Belting Corp. was founded | Thomasnet (2021) |
| 1970s | Coflexip used flexible pipe in offshore applications as flowlines, production and export risers | Sparks (2018) |
| 1972 | SOFEC Inc. was established & IFP France invented high pressure-resistant plastic pipes | SOFEC (2021), Sparks (2018) |
| 1975 | Trelleborg's first OCIMF qualified nippleless hose with dual carcass called KLELINE. | Trelleborg (2018) |
| 1977 | Flexible risers were first used as dynamic risers in Garoupa field, offshore Brazil. | Sparks (2018) |
| 1977 | Yokohama's NBR leak free tube lining, processed by spiral wrapping, completely solved the problems of lining quality, eliminating blisters, lining separation and nipple leak. | Yokohama (2016) |
| 1978 | Yokohama's Polyurethane cover option to the conventional rubber covered hose. The smooth, hard surface of polyurethane eases handling, and its bright colours are its assets. | Yokohama (2016) |
| 1978 | Flexomarine and BLUEWATER were established | Flexomarine (2013), Bluewater (2016) |
| 1980s | IFP developed unbonded flexible pipe using cable industry experience. This led to more Joint Industry Projects (JIPs) on flexible pipes around mid 1980s | PSA (2013) |
| 1981 | Manuli Rubber Industries acquired Fluiconnecto Network (formerly Sonatra) | Fluiconnecto (2021) |
| 1983 | World's stiffest 24″ SRSH (Special Reinforced Submarine Hose) has 51ton-m$^2$ bending stiffness. | Yokohama (2016) |
| 1984 | Super 300 hose – Yokohama's Super 300 hose was developed from total construction analysis by FEM and improved resistance to surge pressure and kinking- high safety margin | Yokohama (2016) |
| 1986 | Fluid-Tec Engineering & Trading Pte Ltd. was established | FluidTec (2015) |
| 1987 | High aromatic hose – Yokohama's high aromatic hose, suitable for liquids with up to 60% aromatic hydrocarbon content, such as high octane gasoline, was developed. | Yokohama (2016) |
| 1992 | Double Carcass hose with Twist Warning System (TWS) – Yokohama style warning system, featuring twist of straight orange stripes on the hose, & warns on failure at primary carcass. | Yokohama (2016) |
| 1994 | 'Friends of Flexibles' ad-hoc JIP of industry operators, manufacturers and material suppliers after the first flexible pipe end-fitting failure at Veslefrikk, due to inner sheath layer failure. | PSA (2013, 2018) |
| 1998 | EMSTEC GmbH was established | EMSTEC (2016, 2021) |
| 1999 | Trelleborg launched REELINE the first large-diameter hose designed for reeling specifically. | Trelleborg (2018) |
| 1999 | Yokohama's Flashing floating hose having effective built-in flashing light unit developed to increase visibility of hose line position to boats nearby especially during night time. | Yokohama (2016) |
| 2001 | Trelleborg developed and introduced the first hose suitable for arctic conditions | Trelleborg (2018) |
| 2004 | Double carcass hose with Dual Warning System (DWS) for primary carcass leak detector. | Yokohama (2016) |
| 2005 | Yokohama's 'Super Stream' Offloading Marine Hose for rough offshore application | Yokohama (2016) |
| 2006 | TANIQ investigated IGW technology for offloading hoses and aeronautic hoses | Nooij (2006) |
| 2006 | Trelleborg launched the first TRELLINE submarine/floating hose that meets API spec 17 K. | Trelleborg (2018), Rampi et al. (2006) |
| 2009 | Trelleborg launched CRYOLINE LNG hose for remote offshore gas fields export via FLNG | Trelleborg (2018) |
| 2009 | Industry standard- OCIMF GMPHOM 2009 was developed. DOM was first to qualify on it. | OCIMF (2009), ContiTech (2014) |
| 2010 | Yokohama Reeling Hose developed for FPSO /FSO reels to resist crush and bending loads. | Yokohama (2016) |
| 2011 | SBM Offshore's Cryogenic Offshore Offloading and Loading (COOL™) system certified | SBMOffshore (2011) |
| 2011 | Trelleborg's first GMPHOM 2009 compliant nipple hose with double carcass, as it increased manufacturing capacity in Brazil for specially designed floating & submarine hoses. | Trelleborg (2012, 2018) |
| 2012 | GMPHOM 2009 Hose – Yokohama's Seaflex series got GMPHOM OCIMF (2009) approval. | Yokohama (2016) |
| 2015 | Trelleborg developed first TRELLINE submarine lines with 600 mm ID that are 2 km long. | Trelleborg (2018) |
| 2016 | Trelleborg introduced first Seawater Suction hose specified to API 17 K designed for FLNG. | Trelleborg (2018) |
| 2017 | Manufacturers supplied suite solutions to world's first floating LNG Ship-to-Shore System | Trelleborg (2018) |

floating hoses, catenary hoses, dredging hoses, cryogenic hoses or reeling hoses (Bluewater 2009, 2020a; OCIMF 2009; ContiTech 2017, 2020a). By functionality, marine hoses are either supply hoses or production hoses. By design, each hose type is designed uniquely for specific functionalities, environments and configurations. The configurations can be ship-to-ship, catenary, lazy-S, steep-S, lazy-wave, Chinese-lantern or tandem configuration (Trelleborg 2016, 2020; Yokohama 2016; Bluewater 2020; ContiTech 2020b). These configurations are adaptable on different offshore platforms and floating structures, like CALM (Catenary Anchor Leg Mooring) buoys and FPSO (Floating Production Storage Offloading) units, as depicted in Figure 1. Recently, Trelleborg presented a Pazflor configuration using treeline OLLs and gimbals (Mayau and Rampi 2006; Rampi et al. 2006; Prischi et al. 2012; Lagarrigue et al. 2014). Generals, hose configurations can be applied on typical different permanent platforms or mobile set ups of dry platforms, moored to a certain location with a network of marine hoses (Stearns 1975; Bai and Bai 2005; Nooij 2006; Sparks 2018; Amaechi et al. 2019a, 2019b, 2021). Additionally, hoses have different sizes, as seen in Antal et al. (2012)'s comparative study, which shows that hoses can also be extremely massive in size, such as the dredging hoses, in comparison to floating hoses, as shown in Figure 2.

This review comprehensively presents the technologies on bonded hoses for marine applications in the offshore industry. Section 1 provides a detailed analysis of the advances in marine bonded hoses

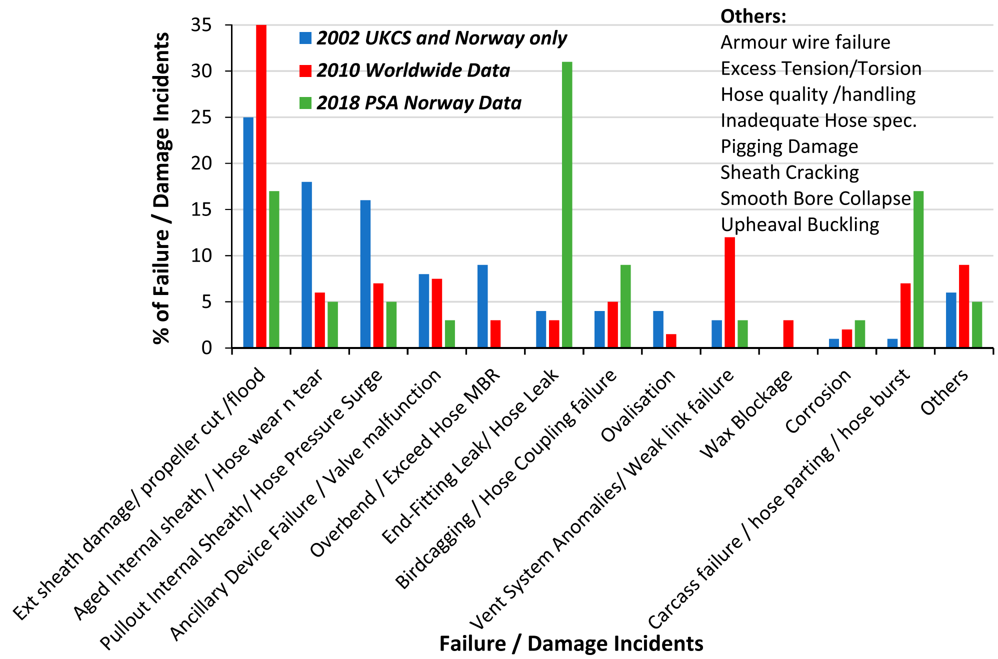


**Figure 3.** Failure and damage incidents on unbonded flexible pipes using 2002, 2010, 2018 data (Sources: Muren 2007; Saunders and O'Sullivan, 2007; Drumond et al. 2018; PSA 2018; Adapted with permission of PSA Norway & Elsevier Publishers) (This figure is available in colour online).

research for these offshore marine applications. Section 2 presents an overview of marine bonded hoses and explores the design of marine hoses. Section 3 presents hose technologies, the application benefits and challenges with explorations on the advances of the useful art (or technology) and patents on marine bonded hoses. Section 4 gives the concluding remarks on hose technologies, sustainable fluid transfer, current gaps and future trends for collaborative synergies.

## 2. Developments on bonded marine hose

In this section, the developments of marine hoses are presented.

### 2.1. Historical development of marine hose

Flexible marine hoses, flexible riser and pipeline technology for offshore oil and gas production still undergo development. Nevertheless, flexible pipes have multi-faceted applicabilities from other sectors before being introduced to the offshore industry. Flexible pipelines were once thought to be maintenance-free and did not need to be inspected on a regular basis. However, recent reports on hose failures, riser failures and flexible pipe failures have shown some reported cases on these facilities and assets offshore. Thus, the need to improve upon the design, manufacture, service delivery processes and production grades. This includes the hoses, pipes, end-terminations, and accessories, which have to be improved however, recent reports also show that significant improvements have been achieved since their initial introduction. The concept of a flexible armoured maritime pipeline was originally introduced and implemented on a large scale in World War II's PLUTO (PipeLine Under The Ocean) project, which transported petroleum from the United Kingdom to Normandy, France, under the English Channel. High-voltage marine power cable technology was used in the design. Today, more progress on marine bonded hose technologies with historical timelines has been recorded, as presented in Table 1. It shows main highlights in marine hose developments, such as Trelleborg launched the first TRELLINE submarine/floating hose that meets API spec 17 K, developed jointly by Trelleborg and SBM Offshore for specific applications, such as OOL (oil offloading lines), deep offshore, flow lines, shallow water and CALM buoy to FPSO (Mayau and Rampi 2006; Rampi et al. 2006; Prischi et al. 2012; Trelleborg 2018). Also, earlier in 1983, the world's stiffest 24-inches Special Reinforced Submarine Hose (SRSH) was developed with a bending stiffness of 500 KN-$M^2$ (51 ton-$m^2$). According to Yokohama (2016), this SRSH is three to four times stiffer than conventional 24-inches hose. This outstanding characteristic contributed to the successful installation of a SALM system for FOSCO at a depth of 45 m (150 ft.) in the Japan Sea.

### 2.2. Overview on marine hose development

Current state-of-the-art hose designs include Selflote- the first integrally floated oil hose, Saflote- the first double-carcass anti-pollution floating hose and DEEPFLO, which are API 17K-specified hoses designed for deep water operations (Antal et al. 2003; Katona et al. 2009; ContiTech 2017). Limited hose patents have also been presented to show advances on marine hose innovations in patent publications and scholarly articles. For instance, Antal Sandor's patents (Horvath et al. 1970; Antal et al. 1985, 1988, 2001) were supported by some scholarly articles (Nagy et al. 1999; Antal et al. 2003; 2012). In Antal et al. (2003), a numerical design on 6-inches bonded flexible riser using FEA was presented with experimental validation, and he concluded by discussing the steps taken to validate the hose in line with the API 17 K standard. However, hoses are rubberised structures as was opined, so one safety apparatus that can be recommended to control hose accidents during offloading operations is the use of pneumatic fenders and other offshore fenders, such as the Inflatable Offshore Fender Barrier Structures -IOFBS (Aboshio 2014; Aboshio et al. 2013, 2014a, 2014b, 2016, 2021). These help to reduce the incidents of hose failure as presented in Figure 3, such as during discharge procedure, and it will also protect these hoses from propeller cuts, damage from tug boats or damage from similar heavy equipment offshore. Although hose failure statistics was not reported in this review, it is recommended to undertake sufficient

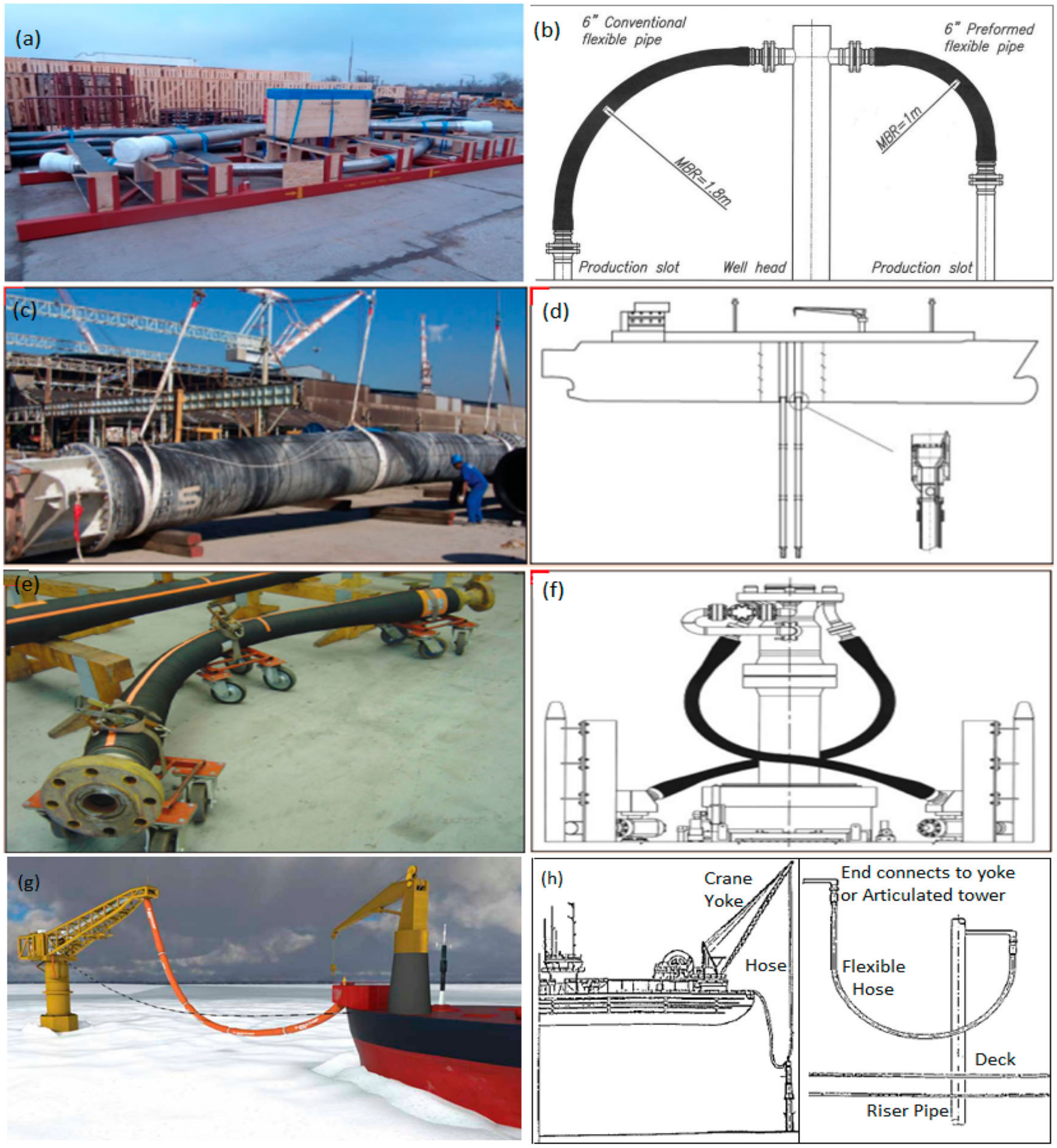


**Figure 4.** Hose developments by Dunlop ContiTech, showing (a) Preformed production lines (b) Conventional and preformed production jumpers (c) Water uptake line removed from Barracuda Oilfield (Brazil) for inspection, ID > 1000 mm, (d) Schematic drawing of a water intake system, (e) TauroBend preformed 3″ (76 mm) 103,4 MPa (15000 psi) bonded Choke and Kill line, capable of 121°C operating temperature and more than 36 MPa collapse pressure, (f) Schematic drawing of the top of subsea blow out preventer (g) API 17 K range of offshore offloading hoses in challenging arctic sea, (h) pile driving application using a pile harmer and a hose from yoke to articulated tower (Adapted with permission of Germa Hornsby of Continental Dunlop Oil & Marine, Sina Leswal and Diana Boenning, both of Heuthig -parent media house of Kautschuk und Gummi Kunststoffe (KGK) publications, and acknowledgement from Nagy Tibor -the author of the KGK publications; Source: Nagy et al. 1998; Katona et al. 2009; ContiTech 2018, 2020b) (This figure is available in colour online).

hose pressure tests because most hose failures involve delamination and carcass failure. Based on the available data for unbonded flexible pipes as seen in the extrapolated '2018 data' obtained from PSA (2018) in Figure 3; it can be noticed that leaks are the most recently reported issues on flexibles, at 31%. The findings are similar to those reported in the literature on failure of flexible risers (Muren 2007; Løtveit et al. 2009; Charlesworth et al. 2011; Dahl et al. 2012; O'Brien et al. 2012; PSA 2013, 2018), flexible pipelines (Muren 2007; Saunders and O'Sullivan 2007; Simonsen 2014; Drumond et al. 2018; Li et al. 2018a, 2018b) and subsea hose systems (Katona et al. 2009,

**Table 2.** Typical list of currently-available hose range (Courtesy: ContiTech 2018).

| Hose Type | Hose ID | Pressure range (psi) | Maximum Available Length | Applicable Certification |
|---|---|---|---|---|
| Production Oil/Has Hose | 2″–14″ | 218 (15 bar) – 7500 | 60 m (2″–8″); 30 m (10″–14″) | API 17K |
| Choke & Kill Hose | 2″–4″ | 5000–15,000 | 60 m | AP 16C |
| Cement Hose | 2″–4″ | 5000–15,000 | 60 m | API 7 K, FSL 0 |
| | 3″ | 20,000 | | Taurus Design |
| Rotary Hose | 2″–6″ | 5000–7500 | 60 m | API 7 K, FSL 1/ FSL 2 |
| | 5″ | 10,000 | | Taurus Design |

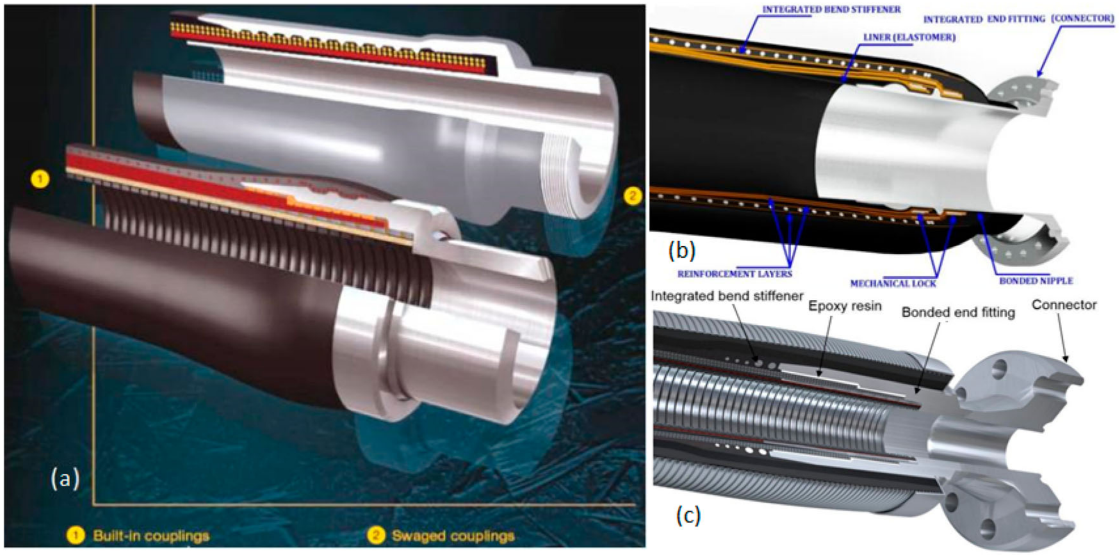


**Figure 5.** End fitting designs showing (a1) end fitting with built-in coupling, (a2) end-fiting with swaged couplings, (c) parts of normal DOM end fitting and (d) parts of DOM End fitting with built-in coupling (Courtesy: Dunlop ContiTech; Adapted with permission of Germa Hornsby of Continental Dunlop Oil & Marine) (This figure is available in colour online).

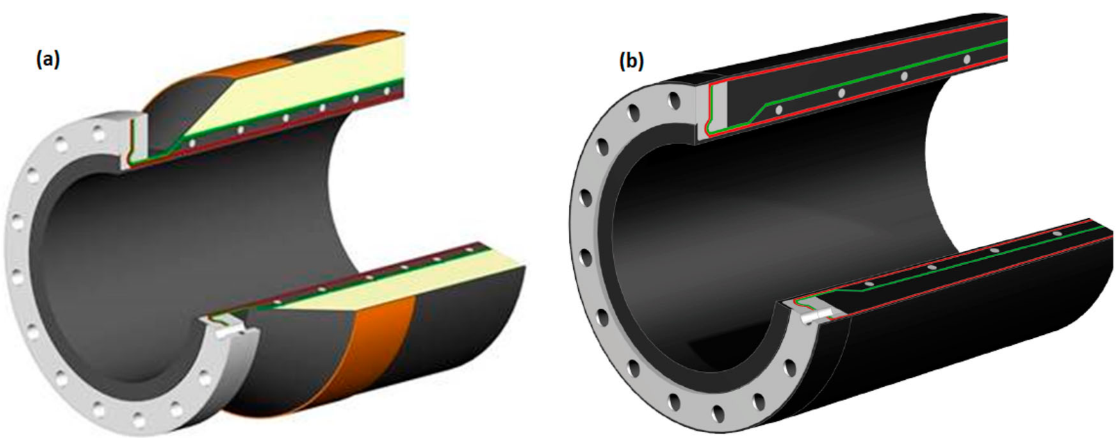


**Figure 6.** Dual carcass reeling hose ends showing (a) reinforced flange/ bolt indent, and (b) nippleless reinforced flange (Adapted with permission of Jonathan Petit of Trelleborg; Courtesy: Trelleborg) (This figure is available in colour online).

**Table 3.** Main components of a typical loading and discharge marine bonded hose.

| Component | Material | Function |
|---|---|---|
| Lining | Super Nitrile | Chemical resistance to fluids carried, sweet crude with 40% max aromatic content |
| Main Reinforcement | Patented Hybrid | Internal pressure resistance, tensile strength and other mechanical attributes |
| Helical Wires | High Tensile Steel | External pressure resistance, tensile strength, kink resistance |
| Binding Wires | High Tensile Steel | Mechanical locking of main reinforcement to end fittings |
| Holding Plies | Patented Hybrid | Cover and extra tensile reinforcement |
| Cover | Rubber/Fabric | Abrasion resistance, ozone resistant, protection for internal bore components |
| Flange | Patented Compact | Interconnection of individual hose lengths |
| Rubber / Metal Bonding System | Proprietary Materials | Chemical bond from fitting to lining / main plies / hose cover |
| Electrical Properties | Continuous or Discontinuous | As specified by client |
| Steel Corrosion Protection System | Rubber Moulding; Special Coating systems as required | Corrosion protection of flange and exposed external metal parts |

*Specification/Guide: API 17 K. Manufacturing Process: Fully Traceable. Service & Fatigue Analysis: Yes. Hose Product Type: Deepflo Submarine lines.
Source: Katona et al. (2009).

Goff and Kay 2015; Serene and Chze 2015). Currently, there are still demands to improve the presently available marine hoses despite applications in deep sea mining (Wang et al. 2009, 2011, 2012; Yang and Liu 2018; Yoon et al. 2009; Yun et al. 2015; Wang et al. 2018). By design, the marine hose is designed to cope with high external pressure loads, due to the elastomeric properties and steel

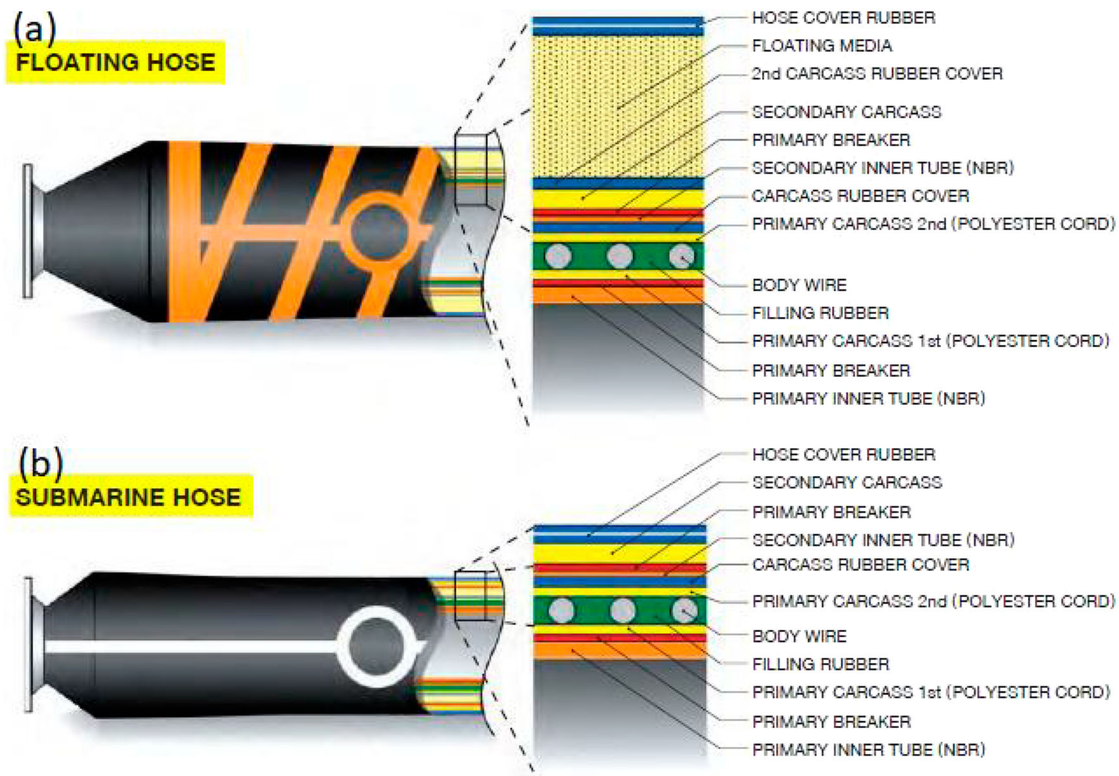


**Figure 7.** Schematic representation of Floating hose and Submarine Hose (Courtesy: Yokohama) (This figure is available in colour online).

**Table 4.** Some manufacturers of API standard marine hoses.

| Manufacturer / Company | Facility Location | Observation |
|---|---|---|
| Coflexip Flexible Products | Duco Inc., UK | Bonded hoses |
| Contitech Rubber (Former Taurus) | Hungary | Bonded hoses |
| Contitech Oil & Gas | Grimsby, UK | Bonded hoses |
| Flexi France | Le Trait, France | Non-bonded hoses |
| Jingbo Petroleum Machinery Company Ltd | China | Non-bonded hoses |
| Yokohama Seaflex | Tokyo, Japan | Bonded hoses |
| Trelleborg | Clermont-Ferrand, France | Bonded hoses |

**Table 5.** Typical hose manufacturing defects with defect rate before 2008 (Courtesy: ContiTech).

| Type of defect | Percentage |
|---|---|
| Defect before FAT test | 0.33% |
| Liner | 0.06% |
| Length | 0.004% |
| Jammed on | 0.004% |
| Esthetical | 0.2% |

reinforcements inside its layers (Lassen et al. 2010, 2014; Gao et al. 2018, 2021; Zhou et al. 2018). While some researched analytically (Knapp 1979; Zhou et al. 2018; Gao et al. 2021) on hose reinforcements, some progress in replacing the steel reinforcement of marine bonded hoses with composite materials were made by Tonatto et al. (2016a, 2016b, 2017, 2019, 2020), by continuing work on earlier models on the same project (Costa 2007; Gonzalez et al. 2014, 2016). However, the fatigue of the reinforcement strength of marine hoses requires more investigation, as gaps in the research trend exist regarding limited articles on hose fatigue (Rampi et al. 2006; Lassen et al. 2010, 2014; Prischi et al. 2012) and helical reinforcements (Knapp 1979; Charlesworth et al. 2011; Cho et al. 2015; Tonatto et al. 2018). As demonstrated in Figure 4, some procedures for hose fatigue solutions and application for hoses as performed by ContiTech Dunlop Oil & Marine (DOM). In locations where a normal flexible hose has difficulty in reaching, it requires preformed hoses with a smaller radius of curvature, as seen in Figure 4(a,b). Thus, these preformed production lines are useful in such tight corners, tight spaces and challenging connections. According to ContiTech (2018), it can be used for hard pipe replacements, as it does not require hot work, painting and has removable pigging loops. It has a typical reduction of MBR by about 50% and can be customised into an array of varying configurations. A typical list of currently-available hose range is given in Table 2.

## *2.3. Hose end-fitting*

The end-fittings of hoses are very essential in the hoseline's composition. With respect to the load transfer mechanisms, these end fittings could have different designs with flange ends, as shown in Figures 5 and 6. End-fittings constitute a significant aspect of the marine hose that also acts as the connection between different hose sections of the hose-string (Huang and Leonard 1989; O'Donoghue 1987; O'Donoghue and Halliwell 1990; Roveri et al. 2002; Zhang et al. 2015; Yokohama 2016; Chesterton 2020; ContiTech 2020a). The mechanics of end-fittings can be seen in studies including submarine hoses and other types of flexibles have led to more advances on hose technologies.

## *2.4. Hose layers*

Marine hoses are designed to withstand different pressure loads, by using different layers as tabulated in Table 3. In principle, the design capabilities of marine hoses can be customised based on specifications which include inner diameter, outer diameter, length of hose,

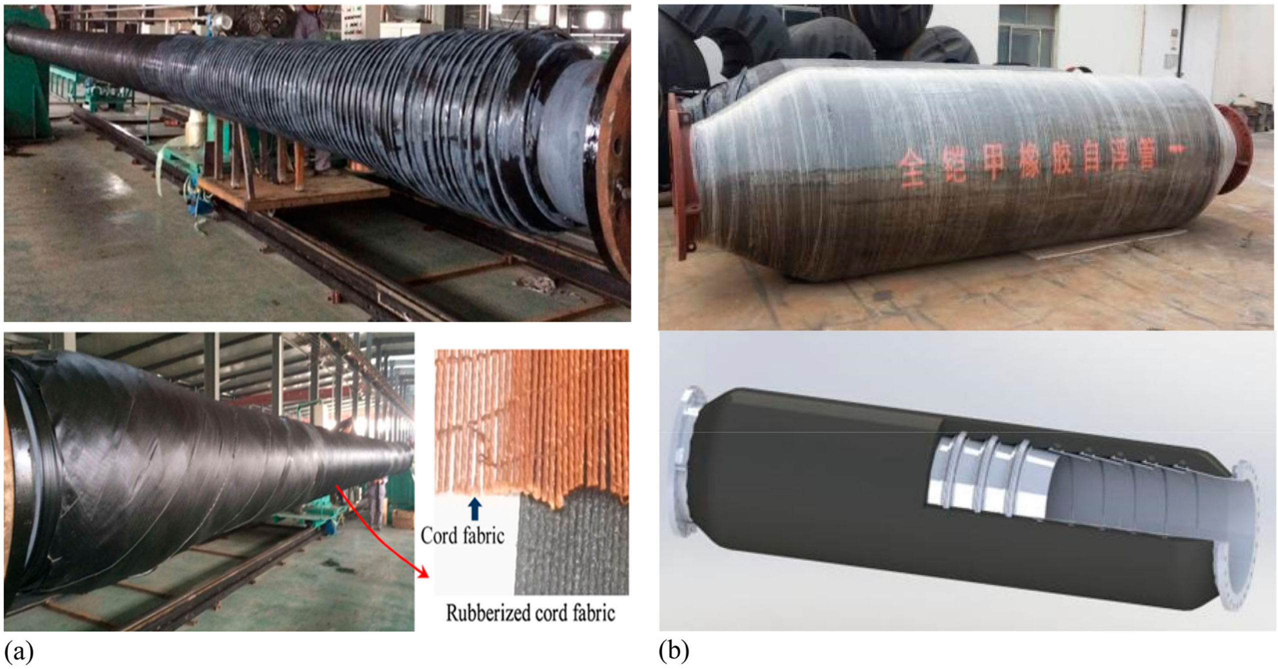


**Figure 8.** Hose reinforcement showing (a) hose reinforcement and elastomer materials on a floating hose, and (b) hose layers, ring stiffened reinforcement and armoured layers of dredging hose (Courtesy: (a) Elsevier Publishers & Gao Q. et al. 2018; (b) Shandong HOHN Group) (This figure is available in colour online).

weight of the hose, colour of hose, tube thickness, working pressure, hose bend radius and the end-fittings. Due to the different hose risers configurations such as the Chinese-lantern configuration, in addition to the aspects of lamination and reinforcements needed on pipelines, risers and hoses, there is the need to have a review on the mechanics of offshore hoses and the hose riser systems. With newer developments in layered pipelines and offshore hoses, the effect of the moment-curvature response, the load response, the D/t ratios of the hoses, the minimum bending radius required, the effect of composite materials and pipeline ovalisation are all important concepts in SURP and have been looked at by different researchers.

Due to the high load requirement of offshore hoses, it is necessary to also carry out numerically investigation. Lassen et al. (2014), presented a finite element model for bonded loading hoses with extreme load capacity assessments and a fatigue life prediction methodology. The bonded loading hoses were subjected to high pressure, tension and bending in a catenary configuration and in repeated reeling under high hose tension. The load effects on the hose during the reeling operations and the fatigue life predictions methodology for both steel components and rubber were emphasised with full scale testing for a 20-inch bonded hose with steel end fittings. Due to the ability of rubber to withstand high deformations, rubberised hoses have been applied in the offshore industry. Different experimental studies on rubber hoses have been carried out on rubber materials (Poisson et al. 2011; Zine et al. 2011) and rubber hoses (Mars and Fatemi 2005; Lassen et al. 2010; Szabó et al. 2017).

### 2.5. Hose manufacture

There are different types of manufacturing processes that are considered in manufacturing bonded hoses. These are considered based on the choice of the materials of the hose, the best manufacturing practices, manufacturers design concepts, manufacturers patents, industry requirements and market demands (Bluewater 2009b, 2011, 2020; EMSTEC 2016; ContiTech 2017, 2020a; HoseCo 2017). Based on the pressure rating and design requirement, the hoses can have a single carcass (SC) or dual carcass (DC), as shown in Figure 7. Currently, different marine bonded hoses have been identified in the market with different product names like Kleeline, Reeline, etc. Also, there are different hose manufacturers (Technip 2006; SBMO 2012; OIL 2014, 2015; Trelleborg 2014, 2016; Yokohama 2016). Some companies that manufacture flexible

**Table 6.** Commonly used elastomers in bonded hoses with the rubber properties.

| | General Properties | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Elastomers | Abrasion | Low Temperature | Weather resistance | Ozone resistance | Heat resistance | Oil resistance | Fuel resistance | Chemical resistance | Petroleum fluid resistance | Aromatic resistance |
| NBR/ Polyvynyl Chloride | | | ++ | + | | ++ | | | | |
| Ethylene propylene rubber (EPR/ EPDM) | | | ++ | ++ | ++ | – | | + | | |
| Styrene Butadiene Rubber (SBR) | ++ | | | | | – | – | | | |
| Isoprene rubber (IR) | ++ | ++ | | | | – | – | | | |
| Natural Rubber (NR) | ++ | ++ | | | | – | – | | | |
| Chloroprene Rubber (CR) | | | ++ | ++ | ++ | + | + | + | + | |
| Nitrile Butadiene Rubber (NBR) | ++ | | | | + | ++ | ++ | | ++ | + |

Note: ++ Excellent property; + Moderate property; – Poor Property.
Source: High Performance flexible hose brochure, ContiTech (2014).

**Table 7.** Material tests recommended by OCIMF (2009) standard.

| Material | Property | Unit | Requirement | Test Method |
|---|---|---|---|---|
| Lining | Tensile strength | MPa | Only Info | ISO 37 |
| Lining | Elongation at break | % | Only Info | ISO 37 |
| Lining | Hardness | IRHD | Only Info | ISO 48 |
| Lining | Density | $gm/mm^3$ | Only Info | ISO 2781 |
| Lining | Resistance to liquids | % | Not greater than 60 | ISO 1817, Method 1. 48hrs at 40°C, liquid C |
| Cover | Abrasion resistance | $mm^3$ | 250 max | ISO 4649, Method A |
| Cover | Resistance to ozone | – | No cracks when magnified at x2 view | ISO 1431-1, 72hrs 50 pphms $O^3$, 10% extension at 40°C and 65% relative humidity |
| Lining | Resistance to temperature | °C | No significant deterioration at −20°C | Gehman test to ISO 1432 |
| Cover | Resistance to temperature | °C | No significant deterioration at −29°C | Gehman test to ISO 1432 |

kill and choke lines, according to API 7 K and API 16CE, are given in Table 4. It is noteworthy to add that the users must check the hose products, though, despite being tested and qualified by industry standards (OCIMF 2009, 2021; Amaechi 2022). However, the introduction of industry standards helped to reduce the manufacturing defects, such as noted in Table 5. During some tests and numerical investigations conducted, it has been observed that an important issue that has arisen is the reinforcement strength during hose designs (Tonatto et al. 2017, 2018; Gao et al. 2018, 2021; Zhou et al. 2018). The hose reinforcement can be a spring spiral or a helical spring or ring-stiffened reinforcement, as shown in Figure 8. The use of a helical Steel framework embedded throughout the riser section and the addition of a rubberised chord fabric wrapped around the sections, as shown in Figure 8, is an excellent approach for further strengthening the riser construction. This assists the riser in dealing with structural loads imposed on it by either external environmental conditions or internal pipeline pressure.

### 2.6. Hose materials

The design of hoses is always carried out with specific considerations on the elastomeric materials (Mars and Fatemi 2001, 2004, 2005; Selvadurai 2006). Common elastomer materials for bonded hoses obtained from manufacturers can be seen in Table 6, which is an example of rubber properties matrix for marine hoses (Mills 2000; Richardson 2004; ContiTech 2018). As is depicted on Figure 8, the hose can be developed using materials made of rubberised cord fabric. However, the materials used should be fully traceable for prototype hose construction and must comply with the quality control procedures of the Hose Manufacturer (Flexomarine 2013; FluidTec 2015; EMSTEC 2016; Yokohama 2016; VHMarineTech 2021). Samples of the materials can be tested in the laboratory, using recommended tests in Table 7, specified in OCIMF (2009).

### 2.7. Hose ancillaries

Hose ancillaries are components that are connected to the hose-string. Among these ancillaries are two important components – the marine breakaway coupling (MBC) and hose end valve (HEV), as shown in Figure 9. The MBC is a device that is installed typically to control flow and discharge under high pressures. It is usually installed unto the hose transfer system at the loading or offshore discharge terminals. The design of MBC helps to prevent oil spills during oil product transfer by parting at pressures lower

**Figure 9.** Two hose systems showing reels, reeling hoses, marine breakaway coupling (MBC) and Hose End Valve (HEV) (This figure is available in colour online).

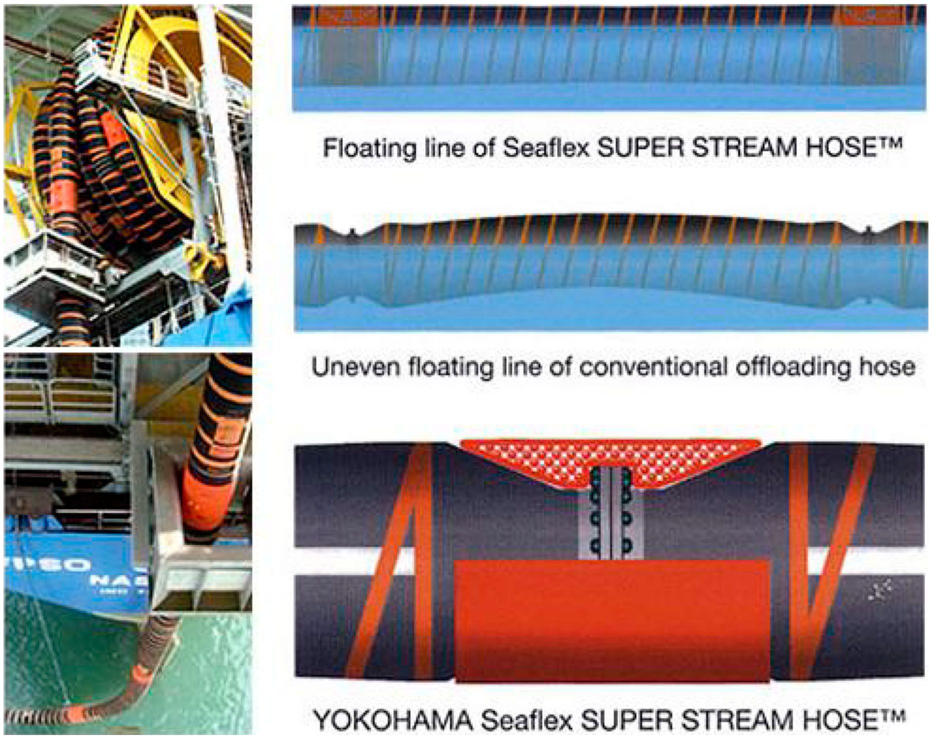


**Figure 10.** Marine hose showing hose coupling (MBC) on floating and reeling hose (Courtesy: Kenwell & Yokohama) (This figure is available in colour online).

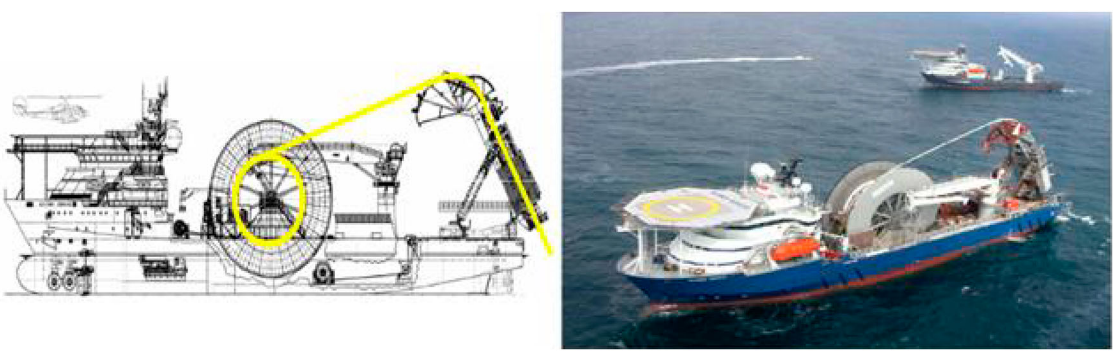

**Figure 11.** Pipe-laying technique called reel-lay using FPSO-mounted reeling drum and reeling hoses (Courtesy: Subsea7) (This figure is available in colour online).

than the burst capacity of the marine hose, which closes gradually in preventing surges due to critical pressures. In a recent report, KLAW (2021) presented the methods of stress reduction on hose reel transfer systems when wound unto hose reels. Another issue identified is that the hose load also could lead to crushing damage on the marine hose when reeled. One approach considered is to optimise the offloading reel drums (Wilde 2016), tensioner reel (Fantuzzi et al. 2019; Chesterton 2020) or to optimise the hose model (Cao et al. 2017; Gao et al. 2018, 2021; Zhou et al. 2018).

Certain considerations are factored in during the design of marine bonded hoses. These include: the type of marine hose, usage, operating environment, the transportation, handling, storage, etc. (OCIMF 2021; Amaechi 2022). Recent designs of hoses, such as the Yokohama's Seaflex Super stream (SS) hose shown in Figure 8, has a special carcass designed with tube lining constructed within the hose by combining specially designed float system. Thus, it makes the hose design to be advantageous in optimised reserve buoyancy, extended durability, better performance, less fatigue on both the hose-manifold and the hoses, and makes it an ideal application for reel-winding systems (Lipski 2011; Abelanet 2012; Kenwell 2021). Generally, most marine bonded hoses are flexible, and can be spools around a reeling system or spooled through to systems, such as during reel-laying, as shown in Figure 10. Due to the application of reeling hoses, such as the pipe-laying vessel depicted in Figure 11, it is crucial to control the flow on the hose. Reeling usually involves some torsion and tensions, which induces some strains on the hoses, as depicted in Figure 12.

## 3. Hose technologies, application benefits and challenges

In this section, the application benefits and challenges were presented.

### *3.1. Configuration of marine bonded hoses*

There are different configurations of marine hoses, as depicted in Figure 13. These configurations are based on different application requirements, environmental conditions, space utilisation and

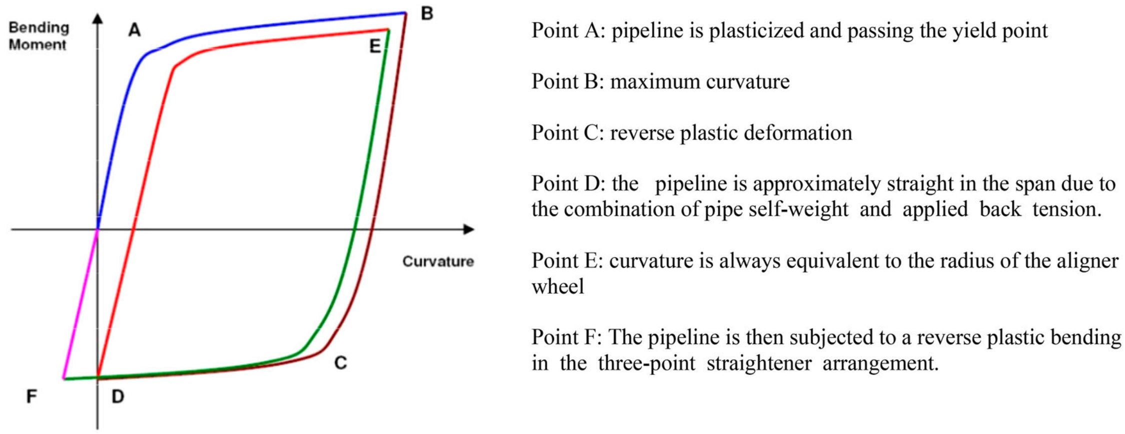


**Figure 12.** Bending moment vs curvature for a reeling hose system (This figure is available in colour online).

design requirement. By design generally, marine hose structures comprise of different sections, as presented in Figures 5–8. However, the pitfall is that some of these hoses have limited usage due to the short service life of the marine hoses of about 25 years (Amaechi et al., 2019a, 2019b, 2021d, 2021e, 2021f), compared to steel marine risers which have vast applications, as reported in various literature on marine risers (Young et al. 1980; Sagrilo et al. 2000; Aranha and Pinto 2001; Bai and Bai 2005; Ali et al. 2020) or much higher service life. A comprehensive review of these systems have been conducted in various studies but did not detail the configuration requirements (Pham et al. 2015; Drumond et al. 2018; Amaechi et al. 2019a, 2019b, 2021b, 2021c, 2021d, 2021e, 2021f). Hence, a review of hose statics and dynamics can be useful in understanding theoretical solutions to the equations of motion of typical marine hose-risers. Amaechi (2022) provided a comprehensive overview of static and dynamic analysis methodologies. Proper computations are required on hose behaviour for different hose-riser configurations, such as the Lazy-S (see Figure 14) and Chinese-lantern configurations (see Figure 15). Some applications with different configurations exist on thermoplastic tubes (Avery and Martins 2003; Picard et al. 2007; Yu et al. 2015, 2017), flexible pipes (Li and Kyriakides 1991; Martins et al. 2003; Lu et al. 2008; Paumier et al. 2009); LNG transfer hoses (Rong-Tai Ho 2008), offloading hoses for $CO_2$ (Brownsort 2015a, 2015b), slurry simulation in spooled hoses (van Rhee et al. 2013), seawater intake hoses (Antal et al. 2003, 2012), ship-to-ship transfer hoses (Rong-Tai Ho 2008; Conti-Tech 2019), composite risers (Sobrinho et al. 2011; Wang et al., 2016; Amaechi and Ye 2017; Amaechi et al. 2019c, 2019d, 2021a, 2022), flexible risers (Sousa et al. 2009; Liu et al. 2013; Ramos 2016), moorings (Ja'e et al. 2022, ALi et al. 2020), and other types of pipelines have led to more advances on this area.

### 3.2. Mechanical property and test methods on hoses

The mechanical property and test methods on hoses are used in different experimental setups conducted, such as the burst test (OCIMF 2009; Yokohama 2016; Gao et al. 2018). Gao et al. (2018) reported that the structural strength of the hose layers, spring reinforcement, and end fittings as critical components of the hose structure using OCIMF (2009) specified tests. Choi and Choi (2015) reported on optimised design variables for carbon-fiber-reinforced epoxy composite coil springs which had a weight reduction above 55%. Chiu et al. (2007) experimentally investigated the mechanical behaviours of helical composite springs. Similar

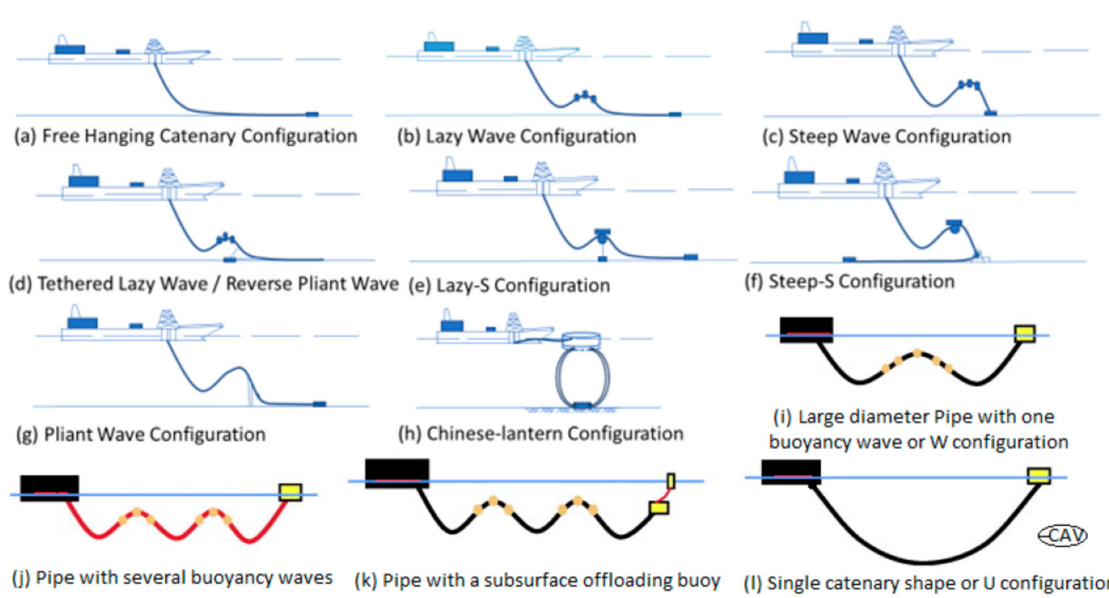


**Figure 13.** State-of-the-art configurations for marine hoses and marine risers (This figure is available in colour online).

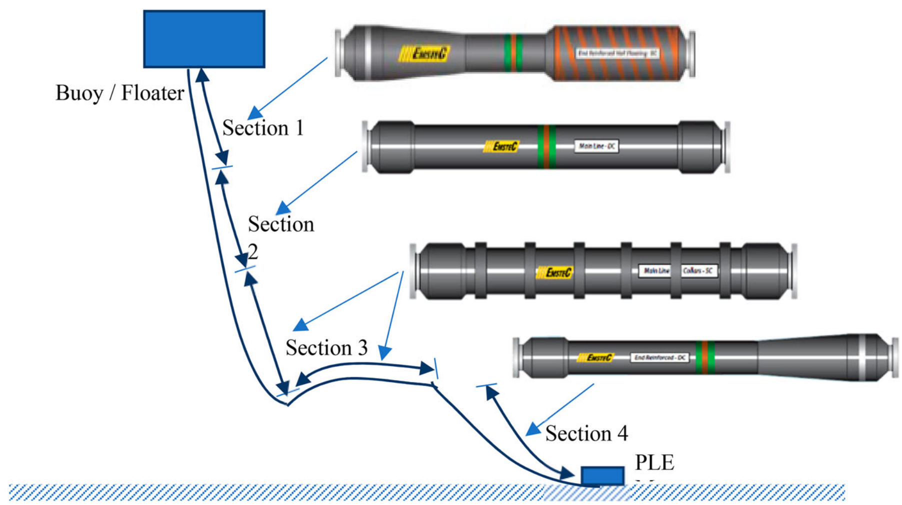


**Figure 14.** Typical depiction of underwater marine hoses in Lazy-S (Hose Image adapted with permission of EMSTEC, but sketch was designed by Author 1- C.V.A; Hose Courtesy: EMSTEC) (This figure is available in colour online).

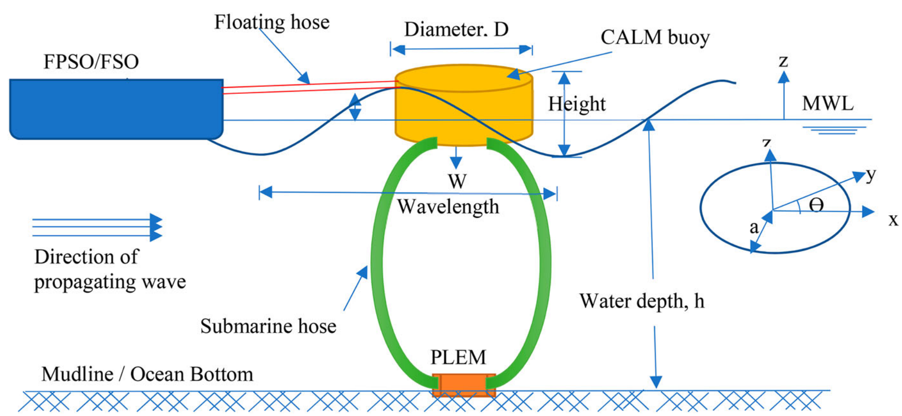


**Figure 15.** Depiction of waves acting upon floating buoy having marine hoses in Chinese-lantern configuration (This figure is available in colour online).

hose spring analysis was carried out numerical on helical spring for high speed valve train and coil collisions (Gu et al. 2020). The study concluded that the FE model can predict the erratic force spikes of the spring at high testing speeds, which cannot be predicted by the conventional analytical model. This is very important in designing hose reinforcements as these offshore hoses are subject to impacts and hose failure modes from high speed boats, tug-boats, offloading FPSOs, and other ancillaries propellers. With recent advances in marine composites, newer conduits are developed like composite risers (Amaechi and Ye 2017, 2021a, 2021b, 2021c), marine bonded composite hoses (MBCH) and Inflatable Offshore Fender Barrier Structures (IOFBS) (Aboshio et al. 2015, 2016, 2021). However, recent reports on inflatable barriers using similar elastomeric hose materials have reinforcements but were not presented in the designs.

Mechanical tests on rubberised hoses, cords and thermoplastics are conducted using different standards like BS 903-5, BS EN 1474-2, ASTM D412-16, ASTM D885, and ASTM E111-04 (BSI 2004, BSI 2008, ASTM 2016, 2014, 2004). From the aspect of mechanical property as tabulated in Tables 5, 6, and 8, different experimental studies on rubber hoses have been carried out on rubber materials (Mars and Fatemi 2001, 2004, 2005; Lassen et al. 2010; Poisson et al. 2011; Zine et al. 2011; Szabó et al. 2017; Milad et al. 2018). Elastomers have been investigated to have different applications in offshore services (Antal et al. 1998, 2003, 2012; Nagy et al. 1999; Katona et al. 2009). However, they also react to harsh environmental conditions (Schrittener et al. 2016; Balasooriya et al. 2018, 2021). Milad et al. (2018) investigated on the hyperelastic material behaviour of a PVC/nitrile elastomer with woven continuous nylon reinforcement composite sheet. It was conducted under loading cases of uniaxial extension and pure shear achieved via wide strip tension testing using a novel advanced non-contact optical strain measurement technique, on an Imetrum system. It was numerically investigated using ABAQUS hyperelastic materials models for modelling the curve fitting (Ali et al. 2010; Motulsky and Ransnas 1987; Ogden 1972; Yeoh 1993), similar to other methods (Ruiz and Gonzalez, 2006; Potluri and Thammandra 2007; Pan et al., 2009). In another study, Aboshio et al. (2015) investigated the mechanical properties of neoprene coated nylon woven reinforced composites experimentally and used ABAQUS material model in the FEA. Earlier experimental works on offshore hoses involved model and full scale tests. Ziccardi and Robbins (1970) presented selection of hose systems for single point mooring (SPM) systems at Hakozaki and Koshiba terminals in Tokyo Bay, Japan for the U.S military. The next year, Dunlop (1971) specified the first offshore hose manual that prescribed the design of hoses, different hose parameters, such as the minimum bend radius, the end connection for the hoses which led to the current GMPHOM

**Table 8.** Property requirements tests for elastomer and metallic materials according to API (Source: API 17K: 2017).

| Materials | Characteristic | Tests | Test methods | Liner | Embedded compound | Cover | Insulation layer | Carcass | Reinforcing layers | Comments |
|---|---|---|---|---|---|---|---|---|---|---|
| Elastomer | Mechanical / physical properties | Tensile strength/ elongation | ASTM D638 | X | X | X | X | – | – | Or ISO 37 |
| | | Stress relaxation properties | ASTM E328 | X | – | X | – | – | – | Swaged end fitting only |
| | | Hardness | ISO 868, ASTM D2583 | X | X | X | – | – | – | Or DIN 53505 |
| | | Compression set | ASTM D395 | X | X | X | X | – | – | Swaged end fitting only |
| | | Hydrostatic pressure resistance | – | – | – | – | X | – | – | Insulation material only |
| | | Abrasion resistance | ISO 4649 | X | – | – | – | – | – | Or DIN 53516. Not required for liner and carcass |
| | | Tearing resistance | ASTM D624 | X | X | X | – | – | – | Or ISO 34–2 |
| | | Void formation | API 17K | X | X | X | – | – | – | – |
| | | Adhesion | ASTM D413 & ISO 4647 | X | X | X | X | – | – | Or BS/ISO 36. |
| | | Density | | X | X | X | X | – | – | – |
| | Thermal properties | Coefficient of thermal conductivity | ISO 2781 | X | X | X | X | – | – | – |
| | | Brittleness temperature | | X | X | X | – | – | – | Or ISO 812. |
| | Permeation characteristics | Fluid permeability | | X | X | X | X | – | – | At design temperature and pressure, minimum to $CH_4$, $CO_2$, $H_2S$ and $CH_3OH$. |
| | | Blistering resistance | | X | X | – | – | – | – | At design conditions, gas service pipes only. |
| | Compatibility and aging | Fluid compatibility | | X | X | X | X | – | – | – |
| | | Aging | | X | X | X | X | – | – | ISO 188 |
| | | Ozone resistance | | – | – | X | X | – | – | – |
| | | Swelling | | X | – | X | X | – | – | – |
| | | Water absorption | | X | – | X | X | – | – | Insulation material only. |
| Metallic materials (carcass strip, reinforcement cables) and weldments | Chemical properties | Chemical composition | ASTM A751 | – | – | – | – | X | X | Or ISO 16120–1 |
| | | Chemical resistance | API 17K | – | – | – | – | X | X | – |
| | | Microstructure | API 17K | – | – | – | – | X | X | – |
| | Strength properties | Erosion resistance | API 17K | – | – | – | – | X | – | Carcass only. |
| | | Fatigue resistance | API 17K | – | – | – | – | – | X | Resistance armour in dynamic applications only. |
| | | SSC (Sour service static) and HIC testing | API 17K | – | – | – | – | – | X | To specified environments; reinforcement armour only. |
| | | Ultimate strength | ISO 6892 | – | – | – | – | X | X | For this purpose, it is equivalent to ASTM A370 |
| | | Yield strength | ISO 6892 | – | – | – | – | X | X | It is equivalent to ASTM A370 |
| | | Elongation | ISO 6892 | – | – | – | – | X | X | – |
| | | Wear resistance | API 17K | – | – | – | – | – | X | – |

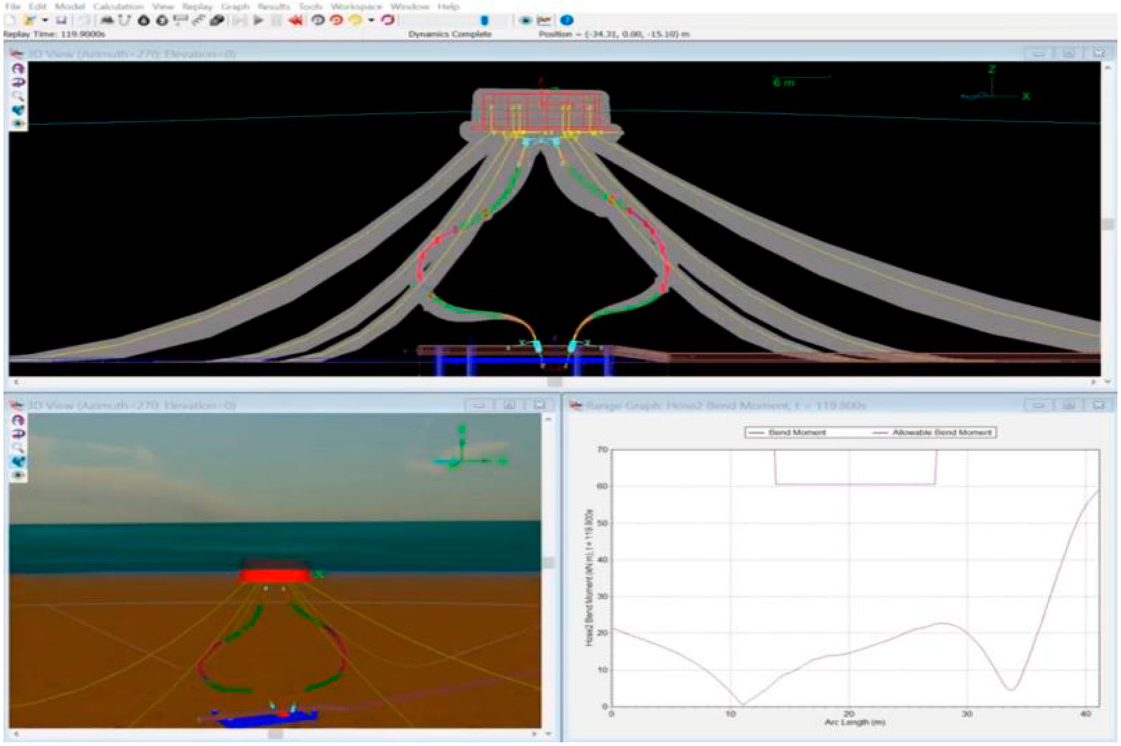


**Figure 16.** CALM Buoy submarine hoses in Chinese-lantern configurations for SPM showing hose bending moment (Courtesy: Stewart B. 2016) (This figure is available in colour online).

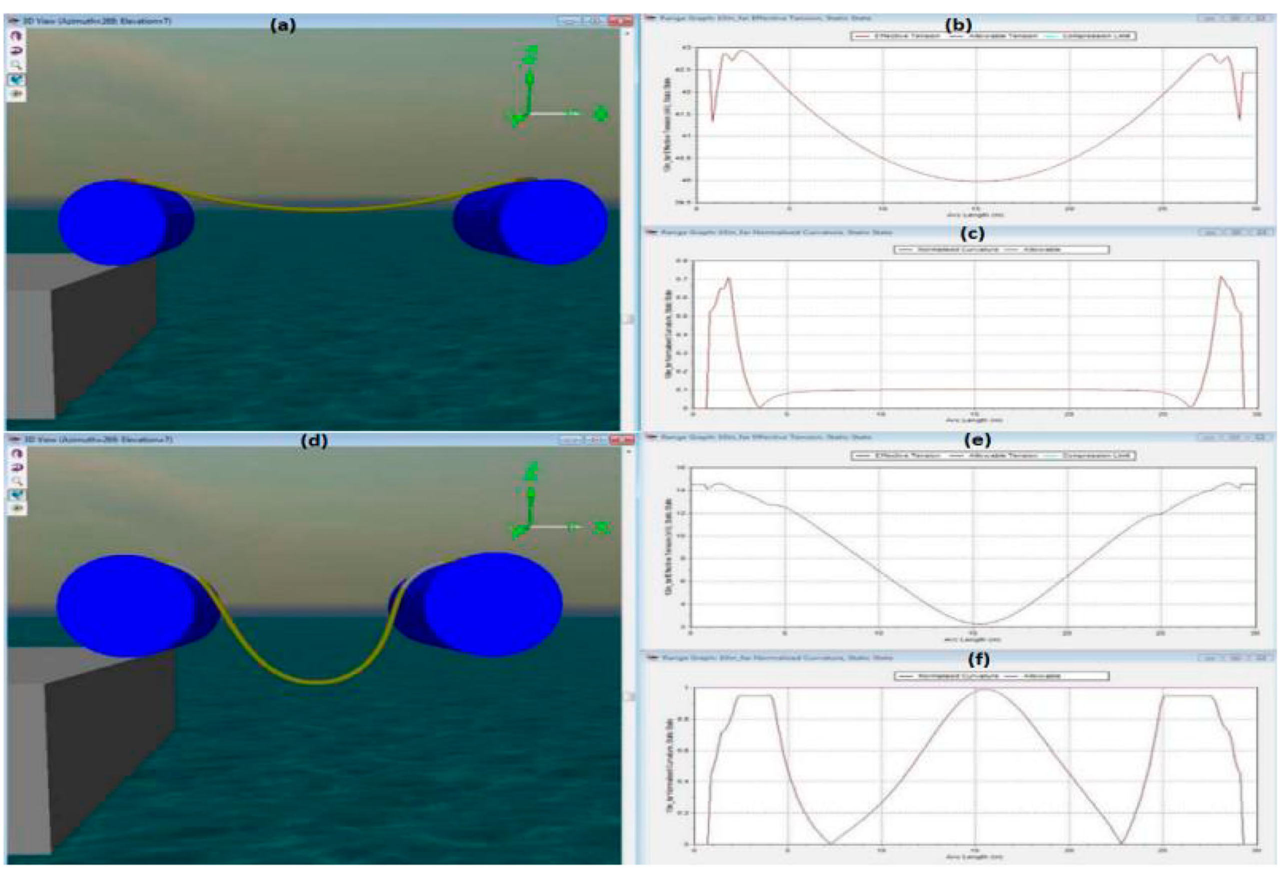


**Figure 17.** Hose configurations showing (a)near hose config., (b) near hose effective tension, (c) near hose normalised curvature, (d) far hose config., (b) far hose effective tension, (c) far hose normalised curvature (Courtesy: Szekely & Peixoto. 2018). (This figure is available in colour online).

**Table 9.** Model tests on CALM buoy offshore hose systems.

| CALM Buoy Description | Year | Model test scale | Reference Company |
|---|---|---|---|
| Porto CALM buoy model tests on shallow water | 2002, 2004 | smaller scale | Single Buoy Moorings Inc. |
| Erha deepwater CALM buoy large scale model tests | 2003 | Scale 1:28.75 | Single Buoy Moorings (SBM) |
| Mooring tests on a shallow water CALM buoy | 1997 | smaller scale | Bluewater, |
| CALM buoy model test | 2002, 2004 | Scale 1: 20 | MARIN (Bunnik et al. 2002; Cozijn and Bunnik 2004; Cozijn et al. 2005) |
| Kizomba SPM model tests | 2002 | Scale 1:60 | Single Buoy Moorings Inc., |
| CALM buoy large scale model tests, | 2001 | Scale 1:20 | Bluewater Energy Services BV |
| DOM's CALM buoy model tests | 1987 | Scale 1:43 | DOM, Heriot-Watt University UK (O'Donoghue 1987; O'Donoghue and Halliwell 1988) |
| Australian North West Shelf CALM | 1996 | smaller scale | Bluewater, |
| Bonga SPM model tests | 2001 | Scale 1:60 | Single Buoy Moorings Inc., |
| Deep draft export buoy model tests | 2002 | Scale 1:60 | Single Buoy Moorings Inc., |
| CALM buoy model tests | 1979 | Scale 1:15 | DOM, Quash & Burgess (Quash and Burgess 1979) |
| CALM buoy large scale model tests | 2004 | Scale 1:20 | Bluewater Energy Services BV, |
| CALM buoy model tests | 2019, 2021 | Scale 1:20 | Lancaster University UK (Amaechi et al. 2019a, 2021h, 2021l; Amaechi 2022) |

**Table 10.** Fatigue test results on OLL offloading marine bonded hoses (Rampi et al. 2006).

| | Damage Prediction | | |
|---|---|---|---|
| Components | Mean | Standard Deviation | Test results |
| Reinforcement steel cables layers | 0.64 | 4.9 | No failure |
| | 0.8 | 5.9 | Failure |
| Longitudinal steel cables in flange area | 1.19 | 20.8 | No failure (2 flanges) |
| | 1.09 | 19.8 | No failure (1 flange) |
| | 1.07 (>2)[a] | 19.1 | Failure[b] (1 flange) |

[a]Figures in brackets gives an estimation of the fatigue damage including vibration contributions, as during the last phase of the tests.
[b]A malfunction of an articulation of the test bench created significant vibrations at the flange connection that failed.

OCIMF (2009), API 17K (2017) and ISO 13628-10 (2006) standards as well as other industry specifications (Trelleborg 2016b; EMSTEC 2016; Bluewater 2020; OIL 2020; ContiTech 2020). Details on the recommended tests on offshore hoses are presented in Table 4. Specifications, such as the buoy manifold design angle at which it bisects with the Mean Water Level (MWL), when it slopes into the water may be at 15° angle (Brown 1985b; Amaechi et al. 2019b), depend on the design. At that position, unusual stress effect is minimal on the first hose due to bending, kinking or premature hose failure. Typical numerical models of hose applications can be seen in the CALM buoy hose configured in Chinese-lantern (see Figures 16) and ship-to-ship hose configuration (see Figure 17).

Based on the hose response, Brady et al. (1974) conducted a full scale test using 60.96 cm (24 in.) hoses attached to a CALM buoy off Nigeria, to measure the forces on the hose at a monobuoy. The authors concluded that the hose problem was due to mainly due to fatigue and less of high stresses. Thus, the need to estimate the strength of hoses to improve hose performance (Saito et al. 1980; Pinkster and Remery 1975; Amaechi et al. 2019a). Saito et al. (1980) studied the external forces that cause kinking on marine hoses was carried out. The study reported measurements by researching on a 50.8 cm (20 in.) floating hose in Tokyo Bay, and observed that the first-off buoy hose resisted fatigue from axial force acting on it, and also resisted kinking due to proper reinforcement. A summarised list of some model CALM buoy tests carried out in various test facilities is presented in Table 5, showing different test models on CALM buoy were carried out in different test facilities using model scales, such as 1:20 for a 20 m diameter buoy at MARIN Wave Tank (Bunnik et al. 2002; Cozijn and Bunnik 2004; Cozijn et al. 2005) and at Lancaster University Wave Tank using scale 1:20 for 10 m diameter buoy (Amaechi et al., 2019a, 2021h, 2021l, Amaechi 2022). The buoy studies included in this review are in Table 9.

### 3.3. Fatigue of marine bonded hoses

In the industry, fatigue calculations for flexible hoses and flexible marine risers have been calculated using different methods like fatigue life estimations, S-N curves and Bending Strength Ratio (BSR) methods (Rampi et al. 2006; Ellis et al. 2008; Lassen et al. 2010; Chibueze et al. 2016). Lassen et al. (2010) carried out a fatigue test and

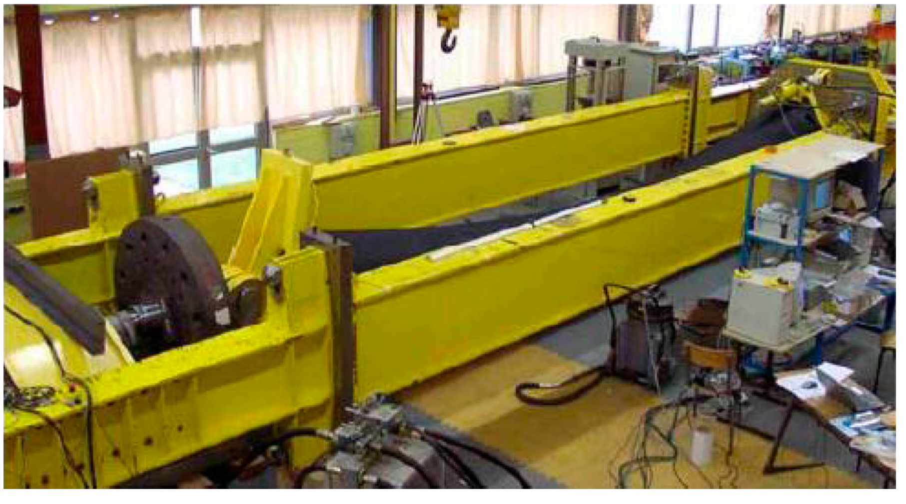

**Figure 18.** Combined bending fatigue + tension using a test bench (Courtesy: Rampi et al. 2006) (This figure is available in colour online).

Table 11. Summary of the reviewed models on marine hoses covering numerical, experimental, fatigue and analytical studies.

| Description | Comment | Model | Ref |
|---|---|---|---|
| Submarine hoses attached to CALM buoy, using Chinese-lantern config. | LM_FEM (lumped mass, finite element model, 3D, ANSYS AQWA, Orcaflex, panel model, line theory | Numerical model | Amaechi et al. (2019a, 2021g) |
| Solid-liquid two-phase flow in slurry pipeline using C4D | two-phase flow velocity measurement, deep-mining pipeline | Experimental model | Yang and Liu (2018) |
| flexible hose in deep ocean mining application | Fluid−solid interaction of resistance loss, FEM, MSC.MARC/MENTAT software | Numerical model | Wang et al. (2012) |
| dynamic analysis of flexible hose connected to deep-ocean mining pipeline | 3D FEM, ANSYS, towing water tank test | Experimental & Numerical model | Wang et al. (2007) |
| Dynamic modelling methods for flexible pipe | RecurDyn, SSM, FDM_LM, RISA_EP | Experimental & Numerical model | Lee et al. (2015a) |
| Numerical modelling of Swaggering process for end fitting and stress relaxation | FEM, Stress relaxation, Contact pressure, End fitting of hose, MARC | Experimental & Numerical model | Cho and Song (2007) |
| Investigation on structural behavior of ring-stiffened composite offshore rubber hose under internal pressure | Experimental, ABAQUS, FEM, burst test on prototype hose, steel helix wire | Numerical & Experimental model | Cao et al. (2017, 2018) |
| High-Pressure Hydraulic Hoses with Steel Wire Braid | Hose deformation on end fitting, hose wire braid reinforcement | Analytical & Numerical model | Rattensperger et al. (2003) |
| Fatigue life assessment of fabric braided composite rubber hose | Complicated large deformation cyclic motion, | Fatigue test | Cho et al (2015) |
| Compressive-tensile fatigue behavior of cords / rubber composites | Experimental test and material testing of rubber hose and cord | Fatigue test | Tonatto et al. (2017) |
| Composite spirals and rings under flexural loading | Material test of composites spirals, MCT model, cohesive zone, | Experimental & Numerical model | Tonatto et al. (2017) |
| On the Fatigue of Steel Catenary Risers | Numerical study, Orcaflex, | Fatigue test | Chibueze et al. (2016) |
| Reinforcement layers in bonded flexible marine hose under internal pressure | theory, parametric study, multilayer composite hose, Mathematica Code | Analytical & Numerical model | Zhou et al. (2018) |
| Ultimate strength, fatigue durability of steel reinforced rubber loading hose, Load response and finite element modelling | Experimental test and material testing of rubber hose, end fitting steel nipple, FEA, hose reeling, rubber material | Fatigue test, Numerical & Experimental model | Lassen et al. (2010, 2014) |
| 12″ 30 m long flexible hoses, ship-to shore LNG transfer | Numerical study, Orcaflex, FEA, Model test, reinforced rubber hose | Numerical & Experimental model | Szekely et al. (2018) |
| 20″ LNG Cryoline floating hose, EN1274-2 qualification; | Full scale, fatigue test, burst test, CFD using STAR-CCM+, Hs of 4m | Numerical & Experimental models | Giacosa et al. (2016) |
| Mathematical Model of a Marine Hose-String at a Buoy | Mathematical model, hose in statics and dynamics. | Analytical model | Brown (1985a, 1985b), Brown and Elliot (1988) |
| vertical bending moments and axial forces in floating hose-strings | Theory of forces on floating hoses Numerical | Analytical & Numerical model | O'Donoghue and Halliwell (1990) |
| Axial behaviour of 20″ bonded flexible marine hose under different loads | Elastomer, REBAR, Steel end fitting, axisymmetric loads | Analytical & Numerical model | Gonzalez et al. (2016) |
| 20″ bonded flexible marine hose under bending loads | Elastomer, REBAR, Steel end fitting, axisymmetric loads, ABAQUS | Numerical model | Gonzalez et al. (2014) |
| Improvement of bonded flexible pipes acc. to new API Standard 17K | Prototype test of 6″ pipe for burst, collapse and axial tests | Numerical & Experimental models | Antal et al. (2003). |

Table 12. Areas of application of marine bonded hoses for transfer, loading and offloading.

| Hose Type | Applications | |
|---|---|---|
| Marine Bonded Hoses | Oil & Petroleum transfer | Abrasive material transfer |
| | Painting transfer | Air, breathing air transfer |
| | Steam transfer | Chemical product transfer |
| | Drain sewer cleaning | Machinery /Vehicle applications |
| | Food transfer | Welding applications |
| | Leisure boat applications | Water applications |

the ultimate strength of steel reinforced rubber loading hose according to API 17B (API 2014a). Fatigue test conducted on the rubberised hoses showed complexly high deformations in cyclic motion. Rampi et al. (2006) investigated on the fatigue of Oil offloading Lines (OOL) – a special marine bonded hoses for offloading, as presented in Table 10, and had some good findings with failure, attributed partly to some vibrations from the test bench, as shown in Figure 18. In another investigation summarised in the hose models in Table 11, Lassen et al. (2014) also presented a fatigue life prediction approach and a FEA for bonded loading hoses with severe loading evaluations, and found that burst pressure affected hose fatigue. Using a catenary design for some repeated reeling under high hose tension, the bonded loading hoses were exposed to severe, bending, tension and pressure.

Figure 19. Installation of floating hoses for a CALM buoy in offshore Brazil (Courtesy: BR) (This figure is available in colour online).

From the investigation, it was observed that reeling has an underlying effect on the hoses, especially the ones close to the helix. Various studies on the fatigue of marine hoses with highlights on their

**Table 13.** Comparative advantages of Trelline OOL hose from technical and commercial aspects.

| Technical advantage | Commercial advantage |
|---|---|
| • Sizes could range to the largest available having practical OOL diameters (smaller winch, smaller horizontal pull, smaller hung weight, smaller SPM buoy, less mooring weight, reduced number of OOL lower Booster Pumping requirement, lower influence on SPM design, etc.)<br>• If there is any damage case, the complete OOL does not require to be changed but just the damaged hose section.<br>• Lighter spread of installation as it requires lesser pulling capacity.<br>• Transport can be done via conventional transportation vessels (liners). | • Lower Offloading OPEX cost (e.g. booster pumping system power consumption and maintenance)<br>• Significant reduction in Overall Deepwater SPM terminal CAPEX<br>• Less Distributed Buoyancy<br>• Lower SPM buoy cost<br>• Flexibility in project execution (installation in phases if required, flexible installation spread)<br>• Lower cost on installation<br>• Lower cost for SPM mooring |

findings are given in Table 11. Various studies on the fatigue of marine hoses with highlights on their findings are given in Table 11. Other types of marine hose investigations exist in literature (Cho and Yoon 2016; Tonatto et al. 2016a, 2017a, 2017b, 2018, 2020).

### 3.4. Application of marine bonded hoses

The application of marine bonded hoses have been identified in other areas, as presented in Table 12. It can be seen that these bonded hoses could be manufactured into different sizes and for different pressure ratings, based on the fluid content, environment and operational conditions. There are also smaller marine hoses, industrial hoses and bigger marine hoses. Hose brands include Dunlop hoses, Parker hoses, Trelleborg hoses, Goodyear hoses, etc. (Trelleborg 2014, 2016, 2018, 2020; Goodyear 2015; Contitech 2018). Applications of offshore hoses have also led to advances in different mooring systems used in towed systems (Schram and Reyle 1968; Sanders 1982; Wang and Liu 2005) and buoy-to-ship hose installation (Amaechi et al. 2021g, 2021h, 2021i, 2021j, 2021k, 2021l, 2021m). The design and engineering of buoys are covered in text (Berteaux, 1976; Berteaux et al. 1977; Harkleroad 1969; O'Donoghue 1987; Irvine 1981; Amaechi 2022). Typical hose installation on a CALM buoy is shown in Figure 19. Some of these hoses require floating hoses and catenary hoses while the others require submarine hoses. However, marine bonded hoses are generally specified according to pressure ratings, like 15bar, 19bar and 21 bars, and standard hose lengths of 9.1, 10.7, and 12.2 m. The application of offshore hoses in the industry have been identified in South China Sea, Bohai Sea, offshore Brazil, offshore Australia, and offshore West Africa, among other seas. It should be noted that waves have been identified to have an effect on these floating structures (Boccotti 2000, 2015; Chakrabarti 1994, 2001, 2002, 2005; Dean and Dalrymple 1991; Holthuijsen 2007; McCormick 2010; Sorensen 1993, 2006). Some investigations on hose applications have also identified different hose behaviour like kinking and snaking phenomena (Bree et al. 1989; Bridgestone 1976, 2017; Piccoli 1976). In this review, the OOL is the particularly chosen hose product for discussing the advantages and technical applications as summarised in Table 13. These application development on the current design of offloading systems have led to advances in various standards like DNV-OS-F101, DNV-OS-FO2, DNV-OS-C201, DNVGL-OS-E403, ABS 2020, ABS 2017 (DNV 2007, DNV 2010, DNV 2014, DNVGL 2015, ABS 2020, ABS 2017).

### 3.5. Patent on marine bonded hoses

Marine hoses can be classified as a type of flexible risers called bonded flexible risers, as flexible risers can either be bonded or unbonded. Despite their typical capacity ratings of 9 and 21 bar, they have a short service life of 5–25 years (Løtveit et al. 2009; Amaechi et al. 2019, 2021a, PSA 2013, 2018), compared to steel marine risers (Young et al. 1980; Sagrilo et al. 2000; Aranha and Pinto 2001; Bai and Bai 2005, 2012). It is noteworthy to state that the service life of marine hoses (like other marine risers) depends on the hose material (Cho et al. 2005, Choi and Choi 2015; Cho and Yoon 2016, the end fitting design (Chen et al. 2016; Pham et al. 2016; Toh et al. 2018), the hose-riser design loads (Chakrabarti and Frampton 1982, Chung et al. 1994a, 1994b, 1981; Chung and Felippa 1981; Dai et al. 2019, Dareing 2012; Sparks 2007), the usage (Amaechi et al. 2021a, 2021b, 2021c), the type of layers -single carcass (SC) or dual carcass (DC) type (Amaechi et al. 2021d, 2021e, 2021f), handling / maintenance (Amaechi et al. 2021g, 2021h,

**Table 14.** Description of different offshore hose ends with the flanges.

| Name of Hose End | Description of Hose End |
|---|---|
| Built-In Nipple Flange (BINF) | During fabrication, a steel nipple is inserted into the hose and connected to the hose body, giving optimum gripping power and an unrestricted transition area. It could be ANSI fixed or floating flanges, but they're best for high-pressure, heavy-duty applications. |
| Built-In Rubber Flange (BIRF) or Duck & Rubber Flange | When mated to a matching flange, a full-face rubber flange is created from extended plies of rubber and produces a liquid-tight seal. It's perfect for transporting abrasive materials under low pressure. Fabric plies and hose tubing wrap around the flange's face. The rubber flange and the steel back-up flange are moulded together. It's best for mild to medium-duty abrasive applications that require minimal pressure. |
| Plain End or Enlarged End | The hose end can be used as a plain hose to fit the pipe's outside diameter, or it can be extended to fit the pipe's outside diameter. |
| Modified Built-In Rubber Flange (Mod BIRF) | Rubber plies and reinforcements from the hose body stretch via the steel nipple and across the surface of the flange, providing a protective barrier against abrasive or corrosive elements. It will provide an unrestricted full flow transition area. It is recommended for full-vacuum servicing and high-pressures. |
| Specialty Ends | Hose ends that have been specifically or custom-designed to meet the demands and standards of designers. |
| Beaded End | Extended rubber plies and reinforcement are used to create a beaded finish. When fastened to a mating flange, split steel back-up rings function as a connecting surface and form a liquid-tight seal. |
| Split-Lok Flange | The developer can generate assemblies in the field using a two-piece reusable coupling system that is attached externally with compression bolts. This is for material transfer hose with a big bore. |
| Rota-Lok | A rubber-lined stub end supports a steel floating flange. This is the best choice for abrasive materials and high-pressure applications. |
| Fixed or Floating Flange | These are drill-bored and ANSI forged steel flanges that are built-in, internally enlarged, or externally swaged. |

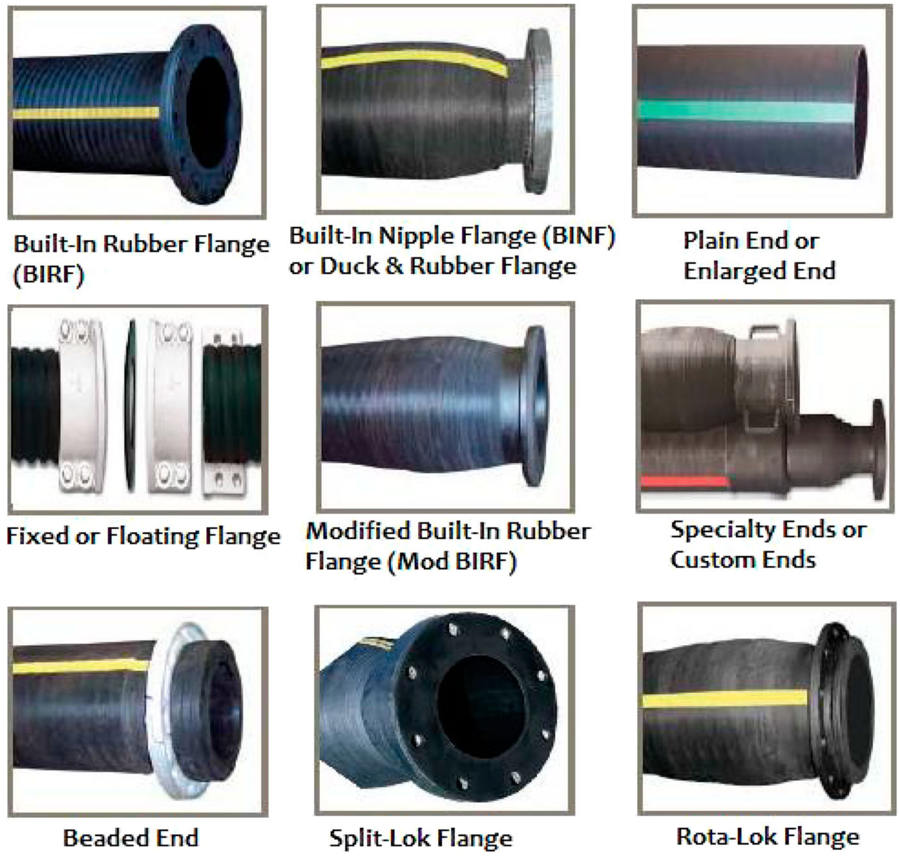


**Figure 20.** Types of hose ends with the flanges (Source: GoodYear) (This figure is available in colour online).

2021i), environmental factors (Amaechi et al. 2021j, 2021k, 2021l), and motion response from vessel (Amaechi et al. 2021m, 2021n, 2021o, 2021p). The development of marine bonded hoses includes different end-fitting design concepts, as in Table 14 and Figure 20. These have led to design patents developed on marine bonded hoses, as presented in Table 15. It shows the progress made in innovating hose technologies in the offshore/ marine industry (ContiTech 2019, Craig 2016; Bluewater 2009a; Gergely and Eduardo 2018; Gong et al. 2014). Other field applications have led to development of monobuoys (Oliveira 2003; Graber et al. 2000; Sweeney 1977), discus buoy (Carpenter et al. 1994), spherical buoys (Zhu and Suk 2016; Zhu and Yoo 2016), spar buoys (Rey and Calvé 2003; Rudnick 1967; Jiang, Li, et al. 2017; Jiang and Ma 2017; Jiang, Zhang, et al. 2017; Katayama and Hashimoto 2015; Kim et al. 2015a; Maslin 2014; Newman 1963), buoy wave converters (Giorgi et al. 2016; Davidson and Ringwood 2017; Kalogirou and Bokhove 2016; Wang 2015) and unique hose-risers called buoy-supporting risers (BSR) (Gouveia et al. 2015a, 2015b; Cruz et al. 2015a, 2015b; Hiller et al. 2015; van Diemen et al. 2015). Aside field developments, there are records of hose applications such as swaging hoses developments (Cho et al. 2005; Cho and Song 2007; Haid et al. 2013; Hayes and Lemond 2013; Kim and Kim 2003a, 2003b), industrial hoses (Kurt 2021; Kwak and Choi 2009; Longmore and Schlesinger 1991), hydraulic hoses (Bridgestone 2017; Patil et al. 2020; Miller and Chermak 1997; SAE 2001, 2008), marine hoses (Mauriès 2014; Minguez et al. 2020; Nooij 2006; Xiang et al. 2013); hose-pipe deployments (Lee et al. 2011a, 2011b; Li et al. 2007, 2019; Ning et al. 2011); hose design approaches (Huang and Leonard 1989, Hong and Hong 1994; Kim et al. 2015b; Lee et al. 2015a, 2015b; Ricbourg et al. 2006), and mathematical modelling (Lenci and Callegari 2005; Obokata 1987; Obokata and Nakajima 1988; Sao et al. 1987; Davidson and Ringwood 2017; Kalogirou and Bokhove 2016; Oh et al. 2014, 2015). In a nut shell, recorded patent developments cut across flexible hoses (Nakane 1935; Castelbaum et al. 1984; Barnard 1938; Baldwin et al. 2000; Asano et al. 1986; Ambrose 1979; Kaiser 1960), rotary hoses (Feier et al. 1950; Goodall 1940), marine hose (Antal et al. 2001, 1989, 1985; Horvath et al. 1970, 1977; Grepaly et al. 2005; Terashima 1996; Yamada 1987); composite pipe (Friedrich et al. 1998; Goddard 1998; Hattori et al. 1989; Quigley et al. 2000; Salama and Mercier 1987; Salama and Spencer 2010; Sas-Jaworsky 1999; Sas-Jaworsky and Williams 1994; Song and Estep 2006), marine riser (Ahlstone 1973; Gallagher 1995; Humphreys 2006; Mungall et al. 1997; Olufsen et al. 1997; Panicker et al. 1984; Pierce 1987; Shotbolt 1988), end-fitting (Langkjaer 2002; Policelli 1989, 1993; Starita 2005; Winzen et al. 1999; Witz and Cox 2013; Witz et al. 2011), pipe coupling (Zeidler et al. 1993), hose coupling (Muller 1941, 1949; Eisenzimmer 1982, Chevalier et al. 1974; Andrick and Brugnano 1997; Anderson et al. 1998; Fisher et al. 1999; Hefler et al. 1992; Maclachlan 1940; Murphy et al. 1979), tanker loading systems (Busch 1987; De Baan and van Heijst 1994, 1991; De Baan 2007; Brown and Poldervaart 1996), oil terminal transfer devices (Remery 1981; Jansen 1981; Isnard et al. 1999; Joubert et al. 1981; Joubert and Falcimaigne 1989; Morgan and Lilly 1974; Schirtzinger 1969; Urdshals et al. 1994), offshore mooring (Coppens and Poldervaart 1984; Briggs 1990; Flory 1976; Hampton 1991), floating buoy system (Braud et al. 1998; Boatman 2003; Nandakumar et al. 2002) and methods of application (Carter 1985; Blanchard and Anastasio 2016; Goldsworthy and Hardesty 1973; Johansson and Johansson 1991; Simmons 1993).

**Table 15.** Patents on development of marine hoses and flexible pipes.

| Patent No. | Reference | Date | Title of Patent |
|---|---|---|---|
| US3,119,415A | Galloway F.M., Kerr R.M., Rittenhouse G.J, Sinnamon R.H. | Jan. 28, 1964 | Buoyant hose |
| US20040012198A1 | Arthur Brotzell, Stewart Fowler, Chanthol Tho | Jan. 22, 2004 | Composite coiled tubing end connector |
| US4887 | Carter J.W. | 1985. | Method and apparatus for longitudinally reinforcing continuously generated plastic pipe. |
| US5579809A | William A. Millward, John Dabinett | Dec. 3, 1996 | Reinforced composite pipe construction |
| US6042152A | Baldwin D.D., Reigle J.A., Drey M.D. | Mar. 28, 2000 | Interface system between a composite pipe and coupling pieces |
| US5520422A* | Ralph Friedrich, Ming Kuo, Kevin Smyth | 1994-10-24 | High-pressure fiber reinforced composite pipe joint |
| US20140216591A1 | Joel Aron Witz, David Charles Cox | 2009-06-02 | Reinforced Hose |
| US20090159145A1 | Aaron K. Amstutz | 2007-12-19 | Hose with composite layer |
| US 8,770,234 B2 | Joel Aron Witz | Jul. 8, 2014 | Hose |
| US20060249215A1 | Bryant, M.J., | 2006. | Anti-collapse system and method of manufacture. |
| US4470621A | Joseph H. Irvine | Sep. 11, 1984 | Flexible tubular connector |
| US5654499A | Dardanio Manuli | Aug. 5, 1997 | Dual carcass flexible hose |
| US8439603B2 | Joel Aron Witz, David Charles Cox | May 14, 2013 | Improvements relating to hose |
| US3769127A | Goldsworthy W., Hardesty E. | 30 Oct., 1973. | Method and apparatus for producing filament reinforced tubular products on a continuous basis. |
| US7523765B2 | Quigley P. A., Feechan M., Wideman T. W. | Apr. 28, 2009 | Fiber reinforced spoolable pipe |
| US3817288A | E Ball | June 18, 1974 | Hose pipes |
| EP0672227B1 | Richards S. J., Reza A., Zandiyeh K. | Sept. 20, 1995 | Hose end fitting and hose assembly |
| US6264244B1 | Isennock C.W., Headrick D. C., Berning S. A. | Jul. 24, 2001 | End connector for composite coiled tubing |
| US 2011/0120636A1 | Bailey S.L., Miller A.K., | 2011-05-26 | Pultruded Arc-Segmented Pipe. |
| US3,905,398A | Johansen H. A.; Philippi L.R.; Green E.A. | Sept. 16, 1975 | Composite reinforced hose wherein the reinforcing material is braided aromatic polyamide filaments |
| US8656961B2 | Chen, B. | 2014. | Composite flexible pipe and method of manufacture. |
| US Patent | Williams, J.G., | 1994. | Dimensional stability. |
| US5908049A | Williams, J.G., Sas-Jaworsky, A., | 1999-06-01 | Spoolable composite tubular member with energy conductors. |
| US5285008 | Sas-Jaworsky A. & Williams J.G. | 8 Feb., 1994. | Spoolable composite tubular member with integrated conductors. |
| US20040012198A1 | Arthur Brotzell, Stewart Fowler, Chanthol Tho | Jan. 22, 2004 | Composite coiled tubing end connector |
| US5988702 | Sas-Jaworsky A. | 23 Nov., 1999. | Composite coiled tubing end connector. |
| US3531143A | Horvath L. Gundisch G., Arvai M., Antal S. | 1970-09-29. | Head-formation of flexible hoses, especially for deep-drilling hoses. |
| US 4,741,794. | Antal S., Smaroglay P., Lantos E. | May 3, 1988. | Equipment for the manufacture of mainly large-diameter flexible hoses having spiralled reinforcement |
| US Pat. 4,120, 324 | Pahl K. H. | 1978-10-17 | High pressure hose composed of elastomers and embedded reinforcements |
| US6315002 US Pat. 6, 831, 002 | Antal S., Gelencsér S., Nagy T., Seregély Z. | 2001-11-13 | High pressure flexible hose structure and method of manufacture |
| US8241453B2 | Bétéri G., Füstöst I., Katona T., Lantos E., Nagy T. | 2009 | Method and apparatus for manufacturing fibre-reinforced hoses |

**Table 16.** Comparison of offloading line with multi-line solution.

| Features | Possible Consequences | Impact on Reliability & Availability |
|---|---|---|
| Reduced flow rate / per line | Reduces failure rate | Positive |
| Two instead of one | Increase probability of impact by external | Negative |
| | Increase inspection effort | Negative |
| | Increase probability of presence of a defect | Negative |
| | Increase probability of damage due to pig run | Slightly negative |
| Proximity | Interaction between lines | Negative |
| | Sensitivity to common mode of failure | Neutral |
| Same type of components | Similar Mean Time to Failure (MTTF) | Neutral or slightly positive |

**Table 17.** Types of hose failures assessed.

| Type of failure | Effects |
|---|---|
| Hazardous Failure | It includes the generation or creation of detrimental physical effects such as heat flux, and blasts. |
| Functional Failure | It is due to the lost of function slightly or completely in a system. |
| Human Management Failure | It is due to poor supervision of the hose-related processes, or poor maintenance of components like hose valves. |

### 3.6. Hazard & risk assessment

Due to the need for safety and to ensure quality compliance, companies like DNVGL and Bureau Veritas (BV) can be contracted to conduct a risk assessment in conjunction with the API 17 K certification programme, as reported by Rampi et al. (2006). A reliability assessment was conducted as presented in Table 16, which shows a rough comparison of a single unloading line against a multi-line solution. A functional examination of the Trelline remote export line system was used to conduct a HAZID (hazard identification) investigation in the first phase. In a second step, an FMECA (Failure Mode, Effects, and Criticality Analysis) is used to provide a qualitative assessment of the primary hazards. Risks related to process and internal fluid (pig deterioration, internal corrosion, etc.), uncontrolled third-party action (dropped object, ship collisions, etc.), sea water environment (marine growth, external corrosion, etc.), and action from interfaces (CALM buoy / FPSO offset, waves, current, etc.) are then examined. There are different types of failures, as presented in Table 17. Once quality compliance is met, there be any circumstance that should be deemed unsatisfactory (criticality level 3). To manage the highest-ranking risks, recommendations are made and implemented (criticality level 2). In terms of system redundancy in the Trelline project, it was reported that special emphasis was paid to comparing a single OOL to a system with several OOLs, which revealed that the benefit of having many OOLs redundant is not assured (Mayau and Rampi 2006; Rampi et al. 2006). The capacity of a system to provide a component with backup in the event of failure is known as redundancy. In order

**Table 18.** Challenge of marine bonded hose failures and some identified causes.

| Cause of Failure | Highlights |
|---|---|
| Kinking at or around the fittings | Once the fitting's barb cuts through the hose tube, the product being transported can escape into the reinforcement, causing the cover to bubble or blister within a few feet of the end. |
| Surging or excessive working pressure | Usually a huge burst at the outside of a bend with shredded reinforcement. |
| Bending a hose past its minimum bend radius | Kinking, crushing, or pushing a hose to bend beyond its minimum bend radius are all examples of this (measured from the inside edge of the hose, not the centreline). This is very prevalent on high-pressure or vacuum pipes. |
| Tube or cover that is incompatible with fluids or the environment | This causes discolouration, swelling, sponginess, or the hose carcass to break down. Always rotate material handling hoses to maintain even wear of the hose tube. |
| Poor craftsmanship or lack or support personnel from hose manufacturer during installation | Hose and fittings are built of a unique blend of diverse materials using sophisticated production procedures – flaws or deviations bigger than permissible tolerances can be caused by human error, inconsistent machinery, or poor product quality or raw materials. Ends blowing off assemblies can be caused by poor coupling techniques or the 'mixing and matching' of mismatched hose, couplings, or clamps. |
| Misapplication | Using a hose, fitting, or clamp for a purpose it was not designed for is one of the most common causes of failure. |
| Temperature Exposure | As the temperature rises, so does the pressure rating. Excessively hot or cold temperatures will cause discolouration, cracking, or hardening, as well as the accumulation of static electricity if the hose wire is not correctly grounded. |
| Hose-line length is too short | Too short a length prevents the hose from expanding and contracting in response to variations in pressure or temperature, putting unnecessary strain on the fittings and hose reinforcement. |
| Defective hose or improperly fitted or selected clamp | Failure from a defective hose, such as pin holes, blow-outs, or tube and cover separation, often occurs in the first few hours of service. The connection can be ejected from the end of the hose due to improperly installed or chosen clamps. Always double-check the manufacturer's recommendations using STAMPED data. |
| Short service life or age-long hose usage | Hose is a flexible component that will degrade over time, as it has material mechanics dependent on different factors. Depending on the composition, application, and environment, the shelf or service life will range from 1 to 20+ years. At low pressures, older hoses grow discoloured, stiff, or burst. |
| Transfer of contaminated media | Foreign particles or residue in the fluid or air might flow through the tube, breaking it down or prematurely wearing it out. Always clean hoses before putting them in the field to avoid cross-contamination. |
| Hose carcass damage from the outside | Kinks, crushed parts, and cover damage that exposes reinforcement will gradually break down the reinforcement, resulting in hose failure. |
| Twisting hose during installation or service | Twisting a hose instead of bending it normally will shorten its life. When putting a hose in a permanent installation, it is estimated that a 7% twist can shorten hose life by 90%. |
| Vessel motion during loading or discharge | During a loading or discharge operation, the vessel is weathervaned or dynamically positioned to avoid oil spills and hose failure or early disconnections. Sometimes, tug boats are used to keep the vessel in position or it will be moored in response to the weather condition. |

to ensure full and robust redundancy, in addition to duplicating the modules, the following recommendations are made:

- non-interference: the existence of redundant components should have no effect on the main one's operation.
- Elimination of common modes of failure: all modes of failure should be avoided. This usually means that the components are separated to prevent them from being exposed to the same damaging effects of external threats.
- Diversification: This requirement aims to avoid the time to failure being of the same order of magnitude because all the components are nominally equal.

### 3.7. Challenges of marine hoses

Presently, marine bonded hose incidents and flexible riser incidents have been recorded and examined in this study (Løtveit et al. 2009, Løtveit 2018; PSA 2018; SureFlex et al. 2010). On hoses for offloading crude oil, there have been a few recorded failures in service, as well as some oil spill incidents during hose loading and transfers. The application, on the other hand, is in great demand, and innovative engineering solutions which have been proposed to address these problems. Marine bonded hoses do experience material damage, failure modes and proprietary design issues, as earlier presented. Although, the necessary checks are done, qualified and verified hoses still under failure which have been identified to be mostly (48%) from hose leaks. It has been gathered that hose manufacturers have been very supported in industry reports such as the PSA state of the art on bonded flexible pipes (PSA 2008, PSA 2018) and for reviewing the standards such as OCIMF 2009, the GMPHOM guidelines (OCIMF 1995a, 1995b, 2009, 2021) and API 17 K rev3 (API 2017). However, the industry requires more statistics and data as feedback from PSA and ITOPF, among other research firms that gather data on the industry. Table 18 shows some identified issues that affect bonded hoses and might lead to hose failure. Aside from challenges on the hoses, there are also other related challenges on different oil fields reported in literature which should also be looked into (Camozzato et al. 2015, Charlesworth et al. 2011, Cao et al. 2015; Bridgestone 1976; Padua et al. 2020; Lebon and Remery 2002; Maneschy et al. 2015; Manouchehr 2012; Szekely et al. 2017). Another challenge in modelling buoy-hose systems include coupling and correctly quantifying hydrodynamic parameters like damping, drag (Le Cunff et al. 2007, Kuiper et al. 2007; Eriksson et al. 2006; Mustoe et al. 1992; Sun et al. 2015). As such, experimental tests, machine learning/trained tests and validation studies are required to improve the design to ascertain the correctness and verify the designs.

### 3.8. Current research gaps & future trends

Different numerical and experimental investigations on marine structures have been a result of collaborations (Graham 1982; Le Cunff et al. 2007; Kang et al. 2014; Duggal and Ryu 2005, Beirão and Malça 2014; Amaechi 2022). These marine structures, particularly the hoses have applications with steel materials. Secondly, these tubulars are multi-layered structures with different material compositions and loads (Fernando et al. 2004; Felippa and Chung 1981; Eggers et al. 2019; Entwistle 1981; Hasegawa et al. 2014; Bernitsas and Kokkinis 1983; De Sousa et al. 2001). Hence, collaborative efforts can be enhanced in this field. One research gap in this subject area is the synergy between academia and the industry, to ensure better research outputs and knowledge exchange on the technology. However, the industry identifies it as a risk with sharing trade secrets, unless NDAs (Non-Disclosure Agreements) are signed. On the other hand, the industry can extend invitations to the academia during their annual seminars, product exhibitions and trainings. It is noteworthy to state that this review is not sponsored by any hose manufacturer, and no input was directly or indirectly given on their products. One key challenge is that industry is not open to share data with academia. On this project as handled in Lancaster University UK, some contacts were made to the industry manufacturers during this review but no response was received, except permissions to use images. Also, their materials were not tested directly on this review, so it was based on performance reports, the available hose brochures and scholarly publications available. A report by PSA (2018) presented some views by two industry manufacturers on marine bonded hoses -Trelleborg and ContiTech /Dunlop Oil & Marine. According to Trelleborg, their hoses for oil product transfers *-REELINE, KLELINE and TREELINE* have proved to be sustainable and effective, from a material point of view. However, there is progress recorded fromn researching its designs with test data, and operational experience. Considering their long track record in the industry for the key players in hose manufacturing, there were no gaps identified, such as in the stability of the material used for hose fabrication. Brindle (2016) and Jonathan Petite (2016) confirmed that the seawater intake hose developed by Trelleborg meets unique demands, and is designed uniquely as it differs from the reeling technology called REELINE and other hose types. Secondly, Trelleborg has a patented nippleless hose end-fitting design which makes its deployment easy to connect and use. Each hose manufacture has a unique design, and mostly patented designs with proprietary materials used in manufacturing the hoses. An example is the uique arrangement of end terminations on Trelleborg products, having compact flange that may include integrated Bending Stiffener when required, as shown in Figure 6. These end-fittings and flanges have passed through rigorous full-scale fatigue tests to predict the behaviour of the end terminations. This happens to be the region that can develop a combination of tension with high bending loads at the domain of the compact flanges. It could also have high pressure zones inside the body based on the hose-riser design or high flow rate of the fluid (Païdoussis 2014; Patel and Seyed 1995; Seyed and Patel 1992; Papusha 2015; Hong and Hong 1994; Amaechi 2022). Hence, it has a gasket that is built-in, to prevent failure with high sealing performance recorded for over 10 years (PSA 2018). One method which is used is to accurately control the pre-tension by torqueing and thus, be able to ascertain any pre-tension during from the composite array of the flanges. Trelleborg also claims never to have reported any bolting failure from their hose products. Good feedback is also necessary as it helps the hose manufacturers to understand the users' preferences. Lagarrigue and Landriere (2017) presented a recent survey report on Trelleborg hoses with focus on preferences of hose users. Such approaches help to attend to the large customer base of these hose manufacturers. Another approach is having Annual Seminars, Quarterly Trainings and User Group Meeting (UGM), which some companies such as Orcina UK – a marine software provide as Orcaflex users support. The software has capability of static and dynamic design of marine hoses, CALM buoys and other floating structures (Orcina 2014, 2019a, 2019b, 2020a, 2020b).

Another issue that could help is sharing information within the industry between hose manufacturers and users. However, it also has risks, due to industry conflicts of interests, trade secret issues, risk of proprietary information and risking manufacturers reputations. Despite that, it would be helpful that there are exchange of information, not necessary trade secret of design knowledge on the useful art, but on best practices. An example is the use of white papers and conference papers, as in earlier MCS software publications (O'Sullivan 2002, 2003; MSCSoftware 2021). The industry will appreciate always having reliable marine hose products that will have longer service life and good failure indication systems. This will in-turn provide improved reliability, more accurate information on the hose service life as well as extensions for different product ranges of the bonded hoses. On the other hand, manufacturers have contrasting views with industry users on some issues. There are still some issues with manufacturer and industry operators unifying on some test limits, such as reducing the test criteria with GMPHOM guideline (OCIMF 2009) for torsion test on marine hoses from 2 deg./m to 1 deg/m. However, hose manufacturers like ContiTech/Dunlop Oil&Marine (PSA 2018) feel that it would be a backward step, which would affect the quality of the hose and can affect the integrity of hose-lines on the offshore structure, when deployed. Earlier standards on rubberised hoses were developed using some ISO standards (ISO 2006, 1997, 2001). Thus, having a unifying standard on marine bonded hoses that is globally accepted is still an issue in the industry, but hopefully these issues will be collated and an updated version of the OCIMF (2009) standard or an ISO, EN, BS, NIS, DNVGL, NORSOK, API, or ABS standard (ABS 2017, ABS 2020; API 2014a, API 2014b, API 2015, API 2017, API 2020; ARPM 2015; Stanton 2014) on marine bonded hoses will be elaborated and published, in the nearest future. From this review, it was also observed that there were limited studies on marine hoses covering vortex-induced vibration (VIV), stability and bifurcation, compared to VIV of marine risers (Hong and Shah 2018) and cylinders (Wu et al. 2012). Hence, future work should include VIV, control and monitoring systems for marine hoses to ensure safety of the asset when deployed. Generally, risers and hoses are subject to different loads which could lead to failure under excessive pressure loads (Pavlou 2013; Sánchez and Salas 2006; Tang et al. 2016). Additionally, failure studies on flexible pipes show that pressure loads, among other factors, influence their behaviour (Neto and Martins 2010, 2012, 2014, Neto et al. 2013, 2016, 2017; Pesce et al. 2010). The failure modes of flexible risers and flexible pipes are available in literature (Li et al. 2018a, 2018b). In contrast, there are limited failure reports on marine bonded hoses. Among the few studies found report failures related to deployment failure (IMCA 2001), hose kinking (Bridgestone 1976) and corrosion of reinforcement (Krismer 2003). Therefore, future works should include hose installation, more methods for reliability analysis of marine hoses systems and stability of related structures in marine applications. Another advantage of the academia to the industry is development of mathematical models for buoys and marine hoses, as seen in some studies (Brown 1985a, 1985b; O'Donoghue 1987; Raheem 2013; Rahman 1981, 1984; Lighthill 1979, 1986). Hence. the expertise of these academicians has been of immense contribution towards the development of CALM buoy hose systems in the offshore industry.

## 4. Conclusion

The development of marine bonded hoses is progressing globally, as has been reviewed herein. The excellent resource potential of marine hoses globally can proffer good incentives for competitive advantages, increased synergies, more collaborations, funding supports, further researches and developments on hose technology and related areas for floating offshore structures (FOS), such as shuttle tankers, turret buoys and CALM buoys. It is noteworthy to state that efficient utilisation of marine hoses in the industry, is usually achieved when suppliers or hose manufacturers provide installation support personnels to ensure the delivery is safe. In this review, the related industry recommendations and standards are examined and evaluated critically. This aids in the identification and provision of the most pertinent verification and validation requirements for the design and manufacture of bonded flexible rubber hoses. This can be employed in a SWIR application if the special requirements of these bonded flexible rubber hoses are taken into account. In addition to transporting untreated seawater, the weights caused by self-weight, vessel motion, and external pressures must be accommodated.

The main highlights of this review are as follows:

- *Overview on offshore industry, sustainable fluid transfer and hose end-fittings.*
- *Historical development, hose design, and manufacturing of bonded marine hoses.*
- *Review on mechanics, hose performance, and assessment of CALM buoy hose systems.*
- *Marine hose configurations, hose modelling, deployment and collaborative synergies.*
- *Application methods for fluid transfer and hose-related sustainable technologies.*

This review avows that the design and manufacture of bonded flexible rubber hoses are governed by some industry regulations and recommendations. While some of these industry rules and recommendations may be implemented, the design and manufacture of bonded flexible rubber hoses for a SWIR application is not particularly covered. It is suggested that it be included in the scope of any future document evaluated or a new SWIR-specific document. As a result of the review, the paper defines the most important criteria and proposes a technique for verifying and validating the design and fabrication of a flexible hose in a SWIR application. Despite the fact that this work presents a set of verification and validation criteria for the design and manufacture of bonded flexible rubber hoses, it does not go into detail about any particular hose type, such as SWIR applications on FPSO vessels. It should also be highlighted that other stakeholders are now considering these technologies for similar purposes. This applies to new Floating Liquefied Natural Gas (FLNG) boats as well as special cylindrical vessels. Although marine bonded hoses have great potentials, the performance reports from scaled tests, and experiments indicate the need for further developments. Competitiveness between hose manufacturer facilities, key performance index (KPI) and product sales competitions between manufacturers has been key indicators that has also driven sales of marine hoses in the industry. Novel devices have been developed to ensure hose monitoring offshore which has also helped in ensuring hose safety, and reduce the recorded incidents of hose failures. Sensitisation is another issue which would help to create synergy between hose users and hose manufacturers. An example is attending industry seminars such as OTC Conferences, ASME/OMAE Conferences, SubseaUK Conferences, Orcaflex User Group meetings and Dunlop Oil&Marine Annual Seminars. This could also help to publicise useful information and share data on user-related information, such as marine hose sales by regions. Lastly, funding researches on marine bonded hoses is another aspect that has affected development of the technology. It was observed that due to the expertise required on hoses, there are very few industry facilities, institutions and research institutes which worked on hoses. This review shows that both the recorded hose manufacturers and academic institutions have research works on marine bonded hoses or related (such as CALM buoys), either in small scale or full scale.

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## Authorship contribution statement

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