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Installation Failures of Flexible and Umbilical Lines

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Abstract

In offshore operations, the installation of flexible lines and umbilicals in producing wells at high water depths is a critical step, since these lines and the installation vessel are subjected to high loads during this operation. As a result, the installation operation must be studied and evaluated before its viability can be determined according to the characteristics of the field and the characteristics of a particular installation ship. During the installation, a series of hydrostatic, pneumatic, and electrical tests need to be made on the installation ship in order to validate and condition the flexible line and umbilical to be used in the offshore field. The main objective of this paper is to present the most common operational failures that occur during installation of flexible and umbilical lines and, the consequences of the damage caused by these failures to the components. These critical failures are explained to determine whether they could cause lose in components functionality in the offshore field and if these failures can cause injury to the workers. The more critical operating faults during the loading, handling, and installation are described and a brief description of each of these failures is presented. The result of this article is a text with illustrations that can serve as a query to interest in the issues related to installations engineering.

Keywords

Maintenance, Security, Risk Assessment

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1. Introduction

The installation of the production and control lines allow for the concession of oil management and, consequently, for the beginning of oil production. Environmental and financial aspects can be profoundly affected by this step, since the installation is subject to delays and accidents between the installation vessel and the platform, and it can cause serious damage to the flexible and umbilical lines, which would make it impossible for functions to be carried out in the field and it can cause injuries to the workers that are doing the installation.

In this way, the installation can financially affect installation companies by means of fines, known as downtime, if the offshore installation is poorly planned and its realization needs to be delayed in comparison with the schedule established previously by the operator or generate damages to the products (lines and umbilicals) or generate financial damages for the operator that fails to produce according to the schedule originally planned.

In addition, installation costs have the highest values (33% of the total project for a production well) compared to the investment values for underwater equipment, flexible lines, umbilicals, and the commissioning period [1].

Among the challenges encountered in the research related to the exploration of oil in deep waters are anchoring analyzed by numerical models, as investigated by Zhao and Liu [2];

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the penetration behavior and trajectory of the drag anchor in seabed soils, explored by Liu et al., [3]; fatigue calculation, as determined by Shiri [4]; and the evaluation of overhead contact lines when installing anchor lines [5-6]. Following the line of research for deformations, there is the application of the analytical method, by Zhu and Cheung [7] and Wang and Chen [8]. In addition, there is the analysis of boundary layers [9].

More specifically, with respect to umbilical cables and flexible pipes, there is the work of Custodio and Vaz [10], which deals with nonlinear models in the study of tension, torque, and internal and external pressures, and more in-depth discussions on the effect of axial deformation on the maximum tension at the shipboard pulley location, from Orsic and Nabergoj [11]. Focusing on tension and drag forces in flexible risers there is a research done by Song et al. [12].

2. Flexible Lines and Umbilicals

Umbilical cables are interconnected from the oil production platform to the Christmas tree or manifold to enable the control, monitoring, and injection of chemicals into the producing well. To perform these important functions, the umbilical has several components, such as hydraulic hoses (thermoplastic), injection hoses (high collapse resistance (HCR), low and high voltage electrical cables, and optical cables. A vertical connection module (VCM) connects the Christmas tree or manifold to the umbilical or flexible line. It is important to know the umbilical behavior under undesirable conditions as explored by Bai et al. [13].

The main umbilical accessories, which may or may not be used during the installation, are the pull-in head, submarine and top armor pot, handling collar, collar stop, stiffening, bending restrictor, splice box, and anchoring collar (Figure 1).

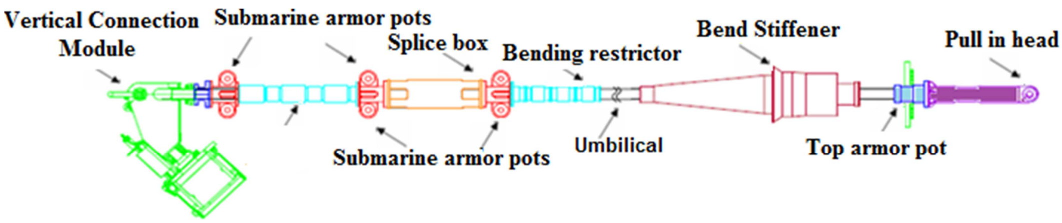

Figure 1. Umbilical accessories [15].

Flexible lines are vital for good production, as they allow the transport of oil components (oil, water, and gas) to the platform for primary processing. They can also be used for gas and water injection into the well, with the aim of increasing the production of wells in which the natural lifting energy has been decreased with the time of production. They are generally composed of polymeric and metallic layers and form a tube with a helical arrangement.

There are two types of flexible lines. The layers of one type are adherent, and there is no slipping between the layers, as vulcanization of the metallic layers occurs in an elastomer matrix. The other type of line has no adherent layers, where the free sliding of its layers occurs. This type of line is the one most used in the offshore segment of Brazil.

The lines that are subjected to dynamic loads of the catenary are denominated risers, and for this reason, they must be projected with internal components passible of high loads of traction and compression, for example. And flexible lines that are only subjected to dynamic loads during an installation, since after an installation, they are under the influence of static charges, such as a hydrostatic pressure, are called flow or flowline.

Next, the internal and external components, as shown in Figure 2, are highlighted, common to a flexible rough wall line.

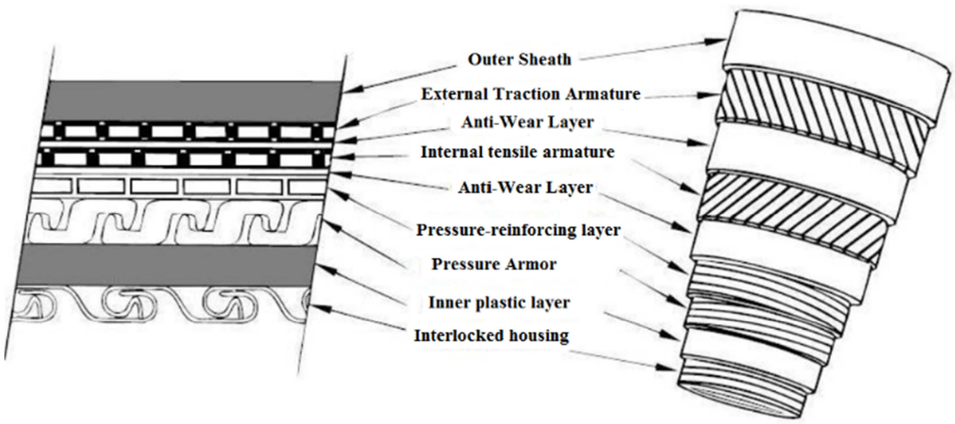

Figure 2. Components of a flexible line of the rough wall [14].

Flexible lines may have specific accessories for each type of interconnection design; for example, hundreds of floats can be clamped in the line to decrease the axial stress of the overhead contact line, or they can be clamped in line with a collar to secure it to a single, large float dimension.

Standard and essential accessories for the flexible line are the connector, pull-in head (Figure 3), stop collar, bend stiffener, bend restrictor, and anchor collar.

The stop collar, stiffener, bend restrictor, and anchor collar have the same main functions as the comparable umbilical accessories, with some minor differences, due to the particularities of the flexible lines. In addition to the top rigging (attached to the bell mouth), there is a rigging at each connector connection between the top risers and intermediate risers.

Figure 3. Pull-in head [15].

For further details on flexible lines and umbilicals, see Schimidt [15].

3. Installation Viability

The problem with submarine cables installation, in particular, the equilibrium-related dynamics and geometric equations, is addressed in several studies, such as Patel and Vaz [6]. One of the critical points of the installation is the mechanical limitations that the cable has [16] and a complete analysis of recovery load must be done [17].

Some possible tests to be done, according to Tayama et al. [18] are the defacing of wire armor test, cable compression test, cable loop test, curvilinear tensile test, and cable colling test.

It is important to highlight international standards that present recommendations that support submarine cable installers such as IEEE Std. 1120/2004 [19].

Other searches analyzing requirements, techniques, and limit parameters in cables for offshore application have been conducted by [20-23].

Before installation, it is necessary to do theoretical calculations and determine if the ship chosen for installation will be able to withstand the loads imposed.

Because the installation towers are long in length (the most current ones can reach almost 70 meters in length), the weight of the line/umbilical in the air must be considered in the calculation of the maximum tensile load. For example, for a tower 70 m long and a flexible line having an air mass of 221 kg/m, we would have a line weight only in the installation tower at be supported by the tensioner around 15 tons.

In addition, it is necessary to add any mass of the umbilical line that was thrown into the sea by the tensioner and to multiply by the line/umbilical length released, which would be the launching water blade in the locality, usually called the LDA or water depth (WD).

The mass of the previously installed accessories (connector, vertebra, traction head, helmet, etc.) and the accessories that will be installed during the launch (anode collars, stop collar, splice box, VCM, etc.) also need to be considered in the calculation. These can be called the mass of accessories.

Thus, Equation (1) presents the calculation formula for maximum axial traction in a given water depth and with a flexible and/or umbilical line not in catenary [15].

$$T_{\max\ inici} = \left[\left(L_{to} + P_a \right) + \left(WD.P_m \right) + P_{ace} \right].A_{grav}.f_{ad} \quad (1)$$

Where:

$T_{max\ inici}$ = Maximum initial axial traction load ($kN=10^3.kg.m/s^2$)

L_{to} = Tower length (m)

P_a = Mass of the line in the air (kg/m)

WD = Water depth (m)

P_m = Mass of the line at sea (kg/m)

P_{ace} = Accessories mass (kg/m)

A_{grav} = Acceleration of gravity (m/s²)

f_{ad} = Dynamic magnification factor (dimensionless).

It is worth noting that, generally, the mass of the flexible or umbilical line, in the air or at sea, considers the line with its annular space to be filled with sea water and the umbilical with the hoses to be filled with hydraulic fluid.

The dynamic expansion factor (f_{ad}) must enter the calculation, due to the meteo-oceanographic conditions that are imposed on the installation vessel during the installation; this value is conditioned by the characteristics of the ship. In the offshore industry, the value of 1.3 to fad has been widely used [24].

Other factors, such as the maximum traction for catenary discharge (Equation 2) and the minimum tightening of the tensioner (Equation 3), in addition to the tightening curves, should be considered in the feasibility analysis of the installation [15].

$$T_{\max cat} = \left[\left(L_{torre} . P_{ar} \right) + \left(LDA . P_{mar} \right) + P_{ace} \right] . A_{grav} \cdot f_{ad} \cdot f_c \quad (2)$$

Where:

$T_{\max\ cat}$ = Maximum axial traction on catenary (kN=10³.kg.m/s²)

f_c = Catenary factor (dimensionless)

$$Ap_{\min} = \frac{T_{\max}}{\mu . N_t . N_l . L_l} \quad (3)$$

Where:

Ap_{min} = Minimum tightening (kN/m/track)

μ = coefficient of friction (dimensionless)

N_t = Number of tensioners (dimensionless)

N_l = Number of caterpillars (dimensionless)

L_l = Effective length of each shoe (m/track)

4. Operating Faults during the Loading, Handling, and Installation of Flexible Lines and Umbilicals

This study addresses the most common operational failures during the loading, handling, and installation of flexible lines and umbilical cables so that, afterward, some suggestions can be made to resolve these operational failures. In this analysis, a structural approach to the failure mode is made. For example, the outer shell component of the line or the umbilical may have failed as the result of a cut, bore, wrinkle, and so on.

In general, the most common faults do not cause serious damage to the products (flexible and umbilical lines), so they can be repaired easily. Recurrent faults are shown first in the flexible lines and then the failures related to umbilicals.

4.1. Damage Occurring in the Flexible Line

There are several types of damage that can occur in the line, such as cutting, bore, wrinkling, and blast of the outer layer. And some damages that do not commonly occur and that possess a great power of destruction of the flexible line include crushing, radial fluctuation (bird cage), twisting (pig tail), and looping.

4.1.1. Damage to the Outer sheath (OS) of the Flexible Line

Outer sheath damage is the most common failure to occur during production line installation; this failure can occur in many situations, and most of these can be avoided. Damage needs to be repaired whenever possible, so that salt water migration to the annular line does not occur and the metal layers do not corrode. The following are the types of failures in the outer sheath:

Puncture cut in the outer layer: The cover of the line can be cut superficially (Figure 4) or deeply (Figure 5), due to sharp surfaces, sharp corners, and an incorrect configuration of the tensioner.

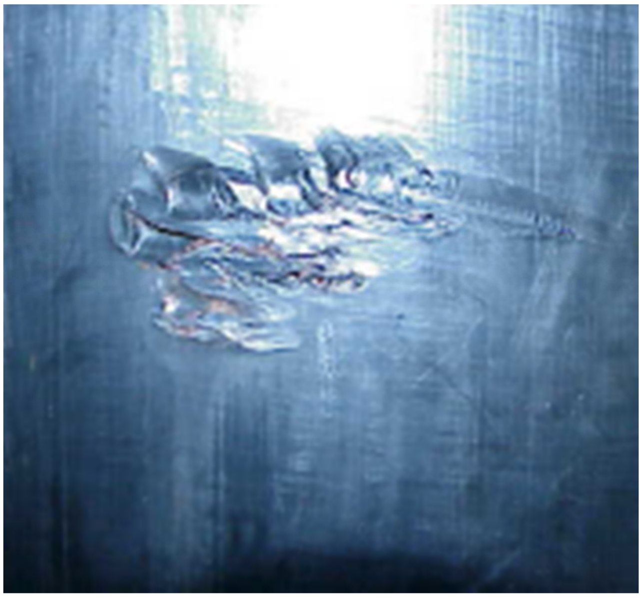

Figure 4. Superficial cut on the outer layer [15].

Figure 5. Deep cut on the outer layer [15].

Longitudinal cut on the outer sheath: The outer sheath can be longitudinally cutted (Figure 6), by a few centimeters or hundreds of meters, on sharp surfaces or sharp corners; it may be due to the lack of synchronism between the launching equipment (tensioner, basket, and coil). If the maximum throw angle on the moon pool is exceeded and the line drags along the edge of the moon pool, there is a great risk of a large longitudinal cut.

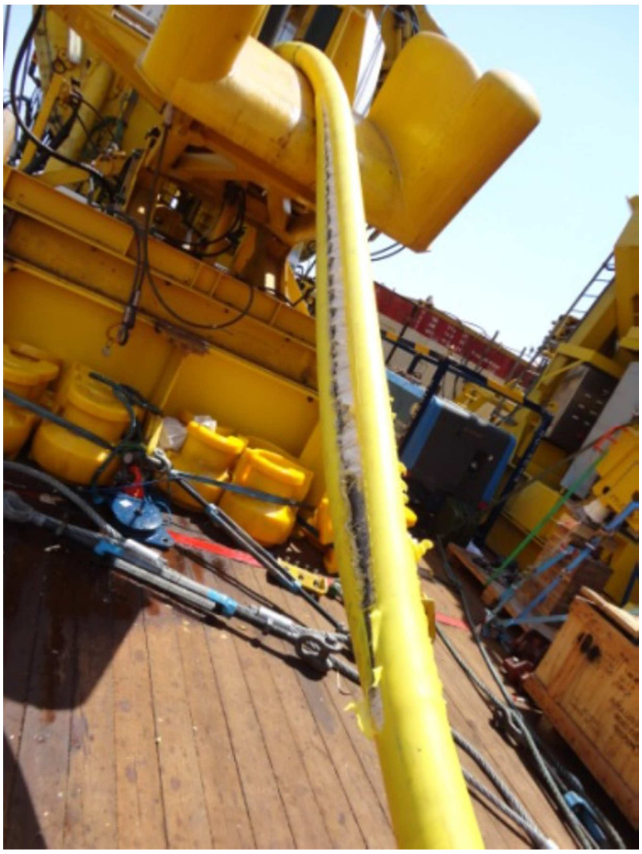

Figure 6. Outer sheath longitudinal cut [15].

Cover Wrinkle: The misconfigured tensioner for a line to be thrown can cause an improper grip and slippage of the line. As a result of this slipping, the line may have its Outer sheath (OS) wrinkled for several meters (Figure 7). Slipping is a critical event, because the tensioner may take a long time to catch a line and, thus, result in an accident.

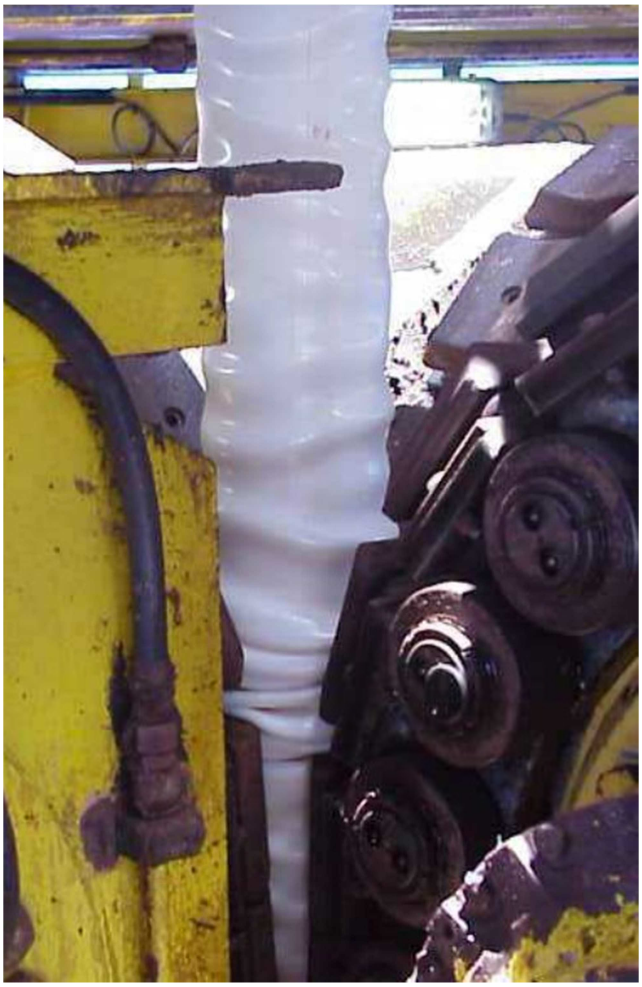

Figure 7. Wrinkling of the outer layer [15].

External Cover Blast: The OS may explode (Figure 8) during line pickup if the gas drain valves are damaged or clogged. During pickup, the pressure in the line submitted at the hydrostatic pressure progressively decreases, and consequently, the pressure difference applied to the outer layer increases. While the pressure differential of the pickup line end is less than an opening pressure of the off valves, there is no risk of the outer casing bursting. When the pressure difference reaches an opening pressure of the valves, there is a risk of bursting, a withdrawal velocity to a considerable extent in relation to the flow capacity of the gas drainage system.

Figure 8. An explosion of the outer layer [15].

4.1.2. Damage to Traction Armor

The traction armature (TA) can be damaged during installation; although this is not a common occurrence, there is the possibility of failure of the flexible line due to this damage.

Traction Armature Cut: If the line is drawn on a sharp surface or a living corner, the cut can overtake the outer sheath and cut the traction armature (Figure 9). It needs to be inspected properly to verify that the cut is superficial and there is no risk of the armature breaking and causing a premature line failure.

Figure 9. Traction armature cutted on surface [15].

Radial buckling: This failure may occur during installation and operation. If the OS and the special aramide tapes are damaged due to the high compressive stresses in the line during the launch, the layers of the traction armature are induced in the opposite direction, which are seated layers; consequently, this fault, radially spaced from the underlying layers and radially open, is known as bird cage (Figure 10).

Figure 10. Radial buckling (bird cage) of the tensile armature [15].

4.1.3. Damage to All Layers of the Flexible Line

The next few failures that will be presented are very serious, as they have the potential to cause damage to all layers of the flexible line and cause it to lose its functionality.

Crushing: The crushing of the layers may occur during launching, whereby radial compressive forces are generated by tightening; if the maximum tightening force limit is exceeded, there will be a permanent deformation at this location of the line (Figure 11).

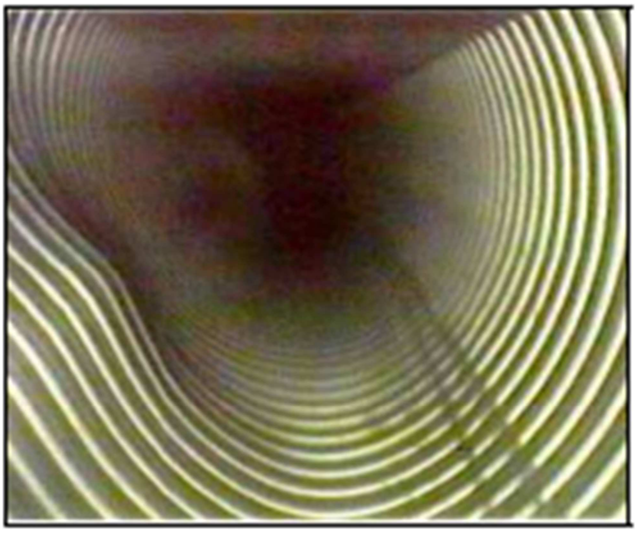

Figure 11. Crushing the layers of the flexible line [15].

In launches made directly from reels or baskets, in which the line passes through a launching wheel or chute, a permanent deformation may also occur if the MBR (minimum bend radius) of the line is infringed on the chute or wheel by a radial crushing force. Crushing may also occur in the storage of the line in the basket if there is an excess weight over the layers, not respecting the maximum tightness of the line (Figure 12).

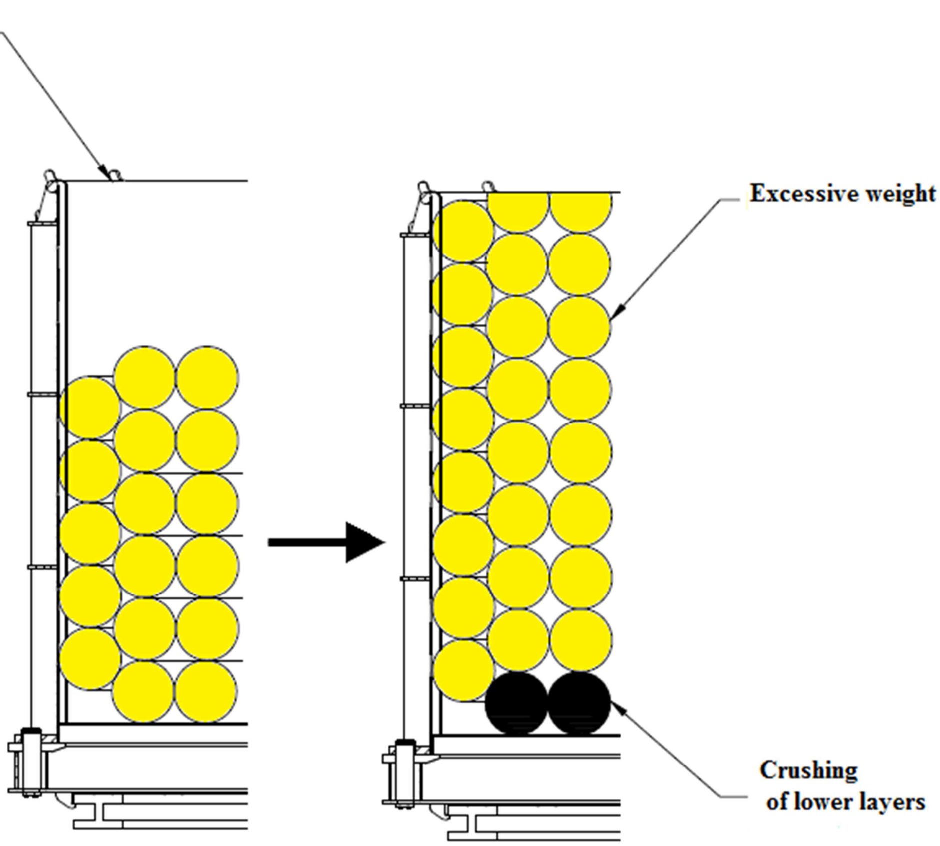

Figure 12. Crushing of the layers due to excessive weight [15].

Torsion: The torsion is the most commonly occurring failure during loading, as the reel twists the line when it is transferred from the reel to the installation vessel. Excessive torsion can occur on the line, as shown in Figure 13. A line will absorb this twist and, if it is within the line's torsional stiffness limit, none of its layers will likely be damaged, but it is common to see cover damage in cases of localized excessive twisting. If the twist exceeds the limit of the torsional rigidity of the line, the line functionality may be affected. In lines of high stiffness, the twist in the line induces a torque that can lead to a torsional deformation. The line may have residual twisting of its manufacturing, and these need to be observed more rigorously during the launch. During the launch, the swivel element installed in the winch socket must be functioning properly. If the line is prevented from turning, it can become twisted (pigtail; see Figure 14) and severely damaged, resulting in a loss of its functionality.

Figure 13. Twisting in the line during loading [15].

Figure 14. Twist (pigtail) in the line during launch [15].

Looping: Looping is characterized by too much curvature in the line, which can occur during loading (Figure 15) due to some type of error in the use of the horizontal loading tensioner, incorrect synchronization of the same, or unexpected stop of the same. At the launch, looping (Figure 16) may occur due to an operational error, but it may be accentuated if the line has residual torsion. At this fault, either the line is bent inside the MBR without danger of damage, or it is bent over the MBR, with great danger of loss of line functionality.

Figure 15. Looping in the loading [15].

Figure 16. Looping at the launch [15].

4.1.4. Damage to Flexible Line accessories

Damage to the fittings of flexible lines can easily occur if certain precautionary measures are not taken and risk analyses are not performed prior to operation.

Damage in the connector: The connector may be kneaded when handled incorrectly, and the sealing area may be damaged. The sealing area may be damaged when cleaned. The protective paint or the anode collar can be damaged from the impact.

Damage in the bend stiffener: The top bend stiffener and intermediate bend stiffener can be easily damaged if they are drawn into the installation vessel's bunkers or are struck against sharp surfaces. The stiffener must not have a cut on it, as this defect can propagate and lead to premature failure of this accessory and the flexible line (Figure 17).

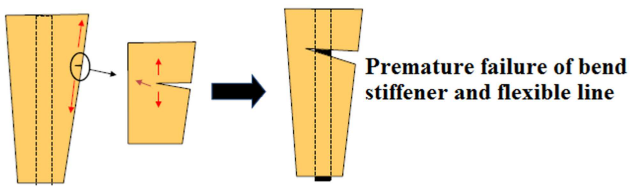

Figure 17. Premature failure of bend stiffener and flexible line [15].

4.2. Umbilical Damage

In general, many of the damages presented for flexible lines are applicable to the umbilicals. For example, the superficial and deep cuts in the outer shell of the umbilical have the same origin as the flex line failure and the same actions and conditions of repair.

Wrinkling of the outer layer of the umbilical also occurs due to a slip of the umbilical on the tensioner. The operational failure caused by slippage and consequent wrinkling of the cap is less likely to occur with the umbilical than the flexible line, though. The actions and mode of repair are equivalent.

Radial buckling more commonly occurs in the umbilicals than the flexible line, due to the characteristics of the umbilical armature wires. Likewise, if the outer shell and the aramid special strips are damaged, the compressive loads on the umbilical during the launch will radially remove the layers of the armature from the underlying layers, causing the failure known as bird cage. The actions and forms of repair are equivalent to those presented for the flexible line.

The umbilical is more susceptible to having its elements crushed in the interior, as it has a maximum tightening load smaller than that of the flexible line, so the umbilical must be released with the pressurized hoses, and the tensioner must always be correctly configured to exceed maximum umbilical clamping. The loading needs to be studied prior to the operation so as not to exceed the weight on top of the layers that will be at the base of the storage basket.

The operational failures restricted to umbilicals will be described below.

4.2.1. Damage to the Hoses

Hoses can be easily damaged during the installation of the umbilical if it comes in contact with any sharp surface or living corner. In this way, the hoses need to be handled correctly when draw heads are being opened, splice boxes are being assembled, and so on.

Hose Cutting/Hole: The hoses may have their outer shells cut off or drilled superficially during their handling at the facility. If the cut or hole is superficial and the layers of aramid are intact, the outer layer can be repaired.

Minimum Bend Radius exceeded: Hoses may have their MBR infringed upon when the ends of the sections are being handled, the splice box is being assembled, and so on. If the MBR is breached, the hose may have its integrity compromised. Normally, an integrity test is done to validate the functionality of the hose. For failing hoses, a replaced connection needs to be made.

4.2.2. Damage to Aramid Layers

The layers of aramid cannot have any kind of damage. If they are damaged by any type of cut or hole (Figure 18) in the thermoplastic or HCR hose, the hose must be replaced so that it does not lose performance and prematurely fail in the field.

Figure 18. Hose punctured deeply [15].

4.2.3. Damage in the Core Tube

The core tube cannot have any cut, bore, or another kind of damage, even if it is only superficial. The small imperfections generated by the damage tend to propagate with the use of the field hose, generating a premature failure of the hose.

4.2.4. Damage to the Umbilical Bending

Generally, the umbilicals have much smaller flexion stiffness when compared to the flexible lines; therefore, the operations of pull-in of the first extremity are much more critical for the umbilicals, since they can undergo a flexion greater than the one supported by it at the moment that the platform winch is picked up (Figure 19), consequently, "breaking" the umbilical. In this case, the umbilical would have to be collected and have be cutted this place, without the possibility of repair.

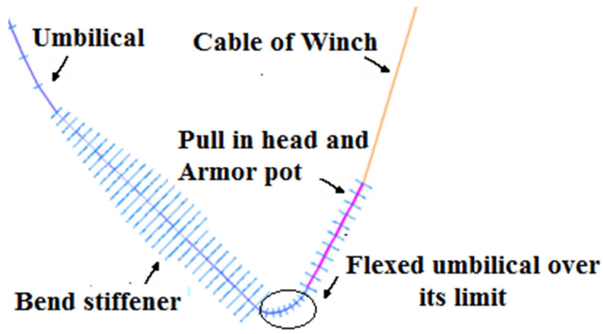

Figure 19. Umbilical flexion above the limit [15].

5. Conclusions

This work highlights that all forms of offshore cable installation need to be studied in advance to assess that viability criteria that determine whether the installation vessel has the ability to withstand loads during the launch, so that the flexible and umbilical lines are not damaged.

The most common failures that can compromise the integrity and functionality of lines and umbilicals during an installation were presented. In general, most operational failures can be avoided if corrective action procedures, risk analyses, and lessons learned are adopted.

It should be noted that the operational failures that were analyzed in this work are not included in any international technical standards on flexible lines and umbilical cables, nor in the academic and doctrinal texts researched. In this sense, the present article contributes to the thematic in question, since it intends to provide an analysis of the usual forms of damage caused during the installation of the main equipment of offshore operations.

References

[1] Bai Y, Lu Y, Cheng P. Analytical prediction of umbilical behavior under combined tension and internal pressure. Ocean Eng 2015; 109: 135-144. doi: 10.1016/ j.oceaneng.2015.08.067.

[2] Zhao Y, Liu H. Numerical implementation of the installation/mooring line and application to analyzing comprehensive anchor behaviors. Applied Ocean Research 2016; 54: 101-104. doi: 10.1016/j.apor.2015.10.007.

[3] Liu H, Liu C, Zhao Y, Wang C. Reverse catenary equation of the embedded installation line and application to the kinematic model for drag anchors. Applied Ocean Research 2013; 43: 80-87. doi: 10.1016/j.apor.2013.08.002.

[4] Shiri H. Response of Steel catenary risers on hysteretic non-linear seabed. Applied Ocean Research 2014; 44: 20-28. doi: 10.1016/j.apor.2013.10.006.

[5] Liu H, Liu C, Zhao Y, Wang C. Comparative study of reverse catenary properties of the installation line of drag anchors. Applied Ocean Research 2014; 48: 42-54. doi: 10.1016/j.apor.2014.07.011.

[6] Patel MH, Vaz MA. The transient behavior of marine cables being laid – the two-dimensional problem. Applied Ocean Research 1995; 17: 245-258. doi: 10.1016/0141-1187(95)00016-X.

[7] Zhu DS, Cheung YK. Optimization of buoyancy of an articulated stinger on submerged pipelines laid with a barge. Ocean Engineering 1997; 24: 301-311. doi: 10.1016/S0029-8018(96)00012-1.

[8] Wang W, Chen G. Analytical and Numerical Modeling for Flexible Pipes. China Ocean Engineering 2011; 25: 737-746. doi: 10.1007/s13344-011-0059-9.

[9] Croll JGA. Bending boundary layers in tensioned cables and rods. Applied Ocean Research 2000; 22: 241-253. doi: 10.1016/S0141-1187(00)00007-9.

[10] Custódio AB, Vaz MA. A nonlinear formulation for the axisymmetric response of umbilical cables and flexible pipes. Applied Ocean Research 2002; 24: 21-29. doi: 10.1016/S0141-1187(02)00007-X.

[11] Orsic JP, Nabergoj R. Nonlinear dynamics of an elastic cable during laying operating in rough sea. Applied Ocean Research 2005; 27: 255-265. doi: 10.1016/j.apor.2006.03.002.

[12] Song LJ, Fu SH, Li M, Gao Y, Ma LX. Tension and Drag Forces of Flexible Risers undergoing Vortex-Induced Vibration. China Ocean Engineering 2017; 31: 1-10. doi: 10.1007/s13344-0001-x.

[13] Bai Y, Bai Q. Subsea Engineering Handbook. Gulf Professional Publishing, 2012.

[14] American Petroleum Institute. API RP 17B - Recommended Practice for Flexible Pipe, 2002.

[15] Schimidt FT. Instalação de Linhas Flexíveis e Umbilicais: Testes de Condicionamento e Falhas Operacionais. Master Dissertation, Fluminense Federal University, Niteroi, 2016. (in Portuguese). doi: 10.13140/RG.2.1.1813.0806).

[16] Feld G, Owen DG. Mechanical behavior of the metallic elements of submarine cables as a function of cable loading. Engineering Structures 1995; 17: 240-253. doi: 10.1016/0141-0296(95)00023-Z.

[17] Yan SW, Jia ZL, Feng XW, Li ST. Umbilical Cable Recovery Load Analysis. China Ocean Engineering 2013; 27: 351-358. doi: 10.1007/s13344-013-0030-z.

[18] Tayama H, Fukuda O, Yamamoto K, Inoue Y, Koike Y. 6.6 kV XLPE Submarine cable with Optical Fiber Sensors to detect Anchor Damage and Defacement of Wire Armor. IEEE Trans on Power Delivery 1995; 10: 1718-1723. doi: 10.1109/61.473389.

[19] IEEE Power Engineering Society. IEEE Std. 1120-2004 – IEEE Guide for Planning, Design, Installation, and Repair of Submarine Power Cable Systems, 2004.

[20] Wald D, Orton H, Svoma R. Requirements for different components in cables for offshore application. Proc 9th Int Conf Properties and applications of Dielectric Materials, Harbin, China 2009.

[21] Choi JK, Nishida S, Yokobiki T, Kawaguchi K. Automated Cable-Laying System for Thin Optical-Fiber Submarine Cable Installation. IEEE Journal of Oceanic Engineering 2015; 40: 981-992. doi: 10.1109/JOE.2014.2363785.

[22] Jin Y, Wan B, Liu D, Peng Y, Guo Y. Dynamic analysis of launch & recovery system of seafloor drill under irregular waves. 2016; 117: 321-331. doi: 10.1016/ j.oceaneng.2016.03.056.

[23] Bawart M, Marzinotto M, Mazzanti G. Diagnosis and location of faults in submarine power cables. IEEE Electrical Insulation Magazine 2016; 32: 24-37. doi: 10.1109/MEI.2016.7528987.

[24] Malcorps A, Felix-Henry A. Validations of a computer model for flexible pipe crushing resistance calculations. Proc ASME 2008 27th Int Conf on Offshore Mechanics and Arctic Engineering. Estoril, Portugal 2008. doi: 10.1115/OMAE2008-57381.