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Abstract

Available literature on offshore mooring is very scattered, unorganized, and available codes and guidelines are very conservative while determining design parameters, such corrosion rate, fatigue factor etc. Mooring design can be optimized by use of more precise design parameters which are based on proven research, field study. Inspection data etc. A study of various design parameters involved in offshore mooring design available from conducted research etc. and comparison with codes, standard and guides. Fatigue failure are one of the critical failure modes. Traditionally only mooring tension are considered in the mooring chain link fatigue analysis. however, for fatigue analysis of mooring chain link, connection to the chain wheels at fairlead, chain link passing over bending shoes , or chain stopper linkers provided by chain hawse or chain stopper, the effect of the out-plane-bending (OPB) on the mooring fatigue should be considered. Since chain typically not coated or protected it is subjected to general corrosion. Splash zone are more potentially for corrosion of chain. To demonstrate the effects of these parameters on strength of mooring chain through a case study. To study the various phase during the life cycle of mooring from design to decommissioning and come up with a kind of a framework covering all important information.

Acknowledgment

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Stavanger, 15th June 2021

Hossein Jafari

Contents

Symbols and Abbreviations

ALS	Accidental limit state
API	American Petroleum Institue
A	Cross-sectional area
A_{eff}	Effective cross-sectional area
A_v	Shear area
COD	Crack opening displacement
CTOD	Crack tip opening displacement
CPS	Cathodic protection system
DNV	Det Norske Veritas
D	Nominal diameter of the link
E	Young’s modulus
EC	Eurocode
FPS	Floating production and storage unit
FPSO	Floating production storage and offloading unit
FEA	Finite element analysis
FLS	Fatigue limit state
F	Axial load
GPS	Global positioning systems
HSE	Health and Safety Executive
h… …	Water depth
IACS	International Association of Classification Societies
ISO	International Organization for Standardization
I	Second moment of area of the whole cross section

JIP	Joint Industry Project
L	Length of the chain link
MBL	Minimum breaking load
MODU	Mobile offshore drilling unit
$M_{pl,Rd}$	Design resistance for bending moment
$M_{N.Rd}$	Design plastic moment
NS-EN	Norwegian Standard European norm
$N_{pl,Rd}$	Design plastic resistance
N_{Ed}	Design value of the axial force
OTC	Offshore Technology Conference
ROV	Remotely operated vehicle
SCF	Stress concentration factor
s	Suspended line length
S_c	Characteristic strength of the body of the mooring line
S_{mbs}	Minimum breaking strength
S	First moment of area about the centroidal axis of the portion of the cross-section
T	Tension in the mooring line
T_H.. ..	Horizontal component of tension
T_{C-mean}	Characteristic mean line tension
T_{C-dyn}	Characteristic dynamic line tension
ULS	Ultimate limit state
V_{Ed}	Design value of the shear force
$V_{pl,Rd}$	Design plastic shear resistance
w	Submerged weight
W_p	Plastic section modulus

X_B..	Length from anchor to touch down point
μ_s	The mean value of the breaking strength of the component.
δ_s	The coefficient of variation of the breaking strength of the component
$\sigma_{x,Ed}$	Design value of the longitudinal stress
$\sigma_{x,Ed}$	Design value of the transverse stress
τ_{Ed}	Design value of the shear stress
γ_{M0}	Partial safety factor
γ_F	Safety factor for fatigue limit state
λ	Normalized variance of the corresponding stress component

1 Introduction

1.1 Background

Available literature on Offshore Mooring is very scattered, unorganized, and available guidelines, standards and codes are very conservative, while determining design parameters such as corrosion rate, fatigue factors etc. Mooring design can be optimized by use of more precise design parameter, which are based on proven research, field test, inspection data etc. Based on the above statement, this report dealing with studying various design parameters, involved in offshore mooring design, available from conducted research, literature etc. and comparison with codes/standards and guidelines for offshore mooring. To demonstrate the effect of these parameters on strength of components through a case study, also studying various phase during the life cycle of mooring from design to decommissioning and come up with a kind of framed work covering all important information.

Fatigue is process of the cycle-by-cycle accumulation of damage in material under fluctuating stresses and strains. When applied load varies with the time, the structure can subject to fatigue failure. Fatigue is one of the critical failure modes of offshore permanent mooring systems. Fontaine et al. [21] reviewed 107 offshore mooring accident and find out that the 29 mooring accident are primarily due to fatigue. Traditionally, only mooring tensions are considered in the mooring chain fatigue analysis. However, for fatigue analysis of mooring chain link, connecting to the chain wheels at fairlead, chain link passing over bending shoes or chain linkers provided by chain hawse or chain stopper the effect of the out-of-plane bending on mooring fatigue should be considered.

Offshore structure subjected to harsh and corrosive environment during their lifetime. Since chain is typically not coated or protected, it is subjected to general corrosion. This lack of protection is typically accounted for in design by imposing a wear and corrosion allowance on the chain. Splash zone are more potentially for corrosion of chain.

Along the mooring line, there are few areas that are prone to integrity issues. These are need special attention during inspection. Top end at the vessel interface and touch down area at the seabed are problematic areas. They are subjected to high degradation and need closely inspected. All connectors and wire rope termination are critical components because discontinuity in weight per length can increase bending and wear. According to several studies, chains failure contributes 47% of the incidents from year 2001 to 2012. After the chain, connectors from and wire represent high rate of failures. Polyester rope represents only 5% of the failure. Most chain failure is because of corrosion and fatigue. Most of failure of the chain failure occurred in upper sections and stopper/fairlead. This indicated that the indicated that behavior of chain links in this region should be carefully evaluated during design, to reduce the risk of failure. Wire rope failures were most in termination, this indicated that local behavior at mass/stiffness discontinuities at wire termination carefully evaluated during design, to minimize the risk of failure.

1.2 Objectives

To study various design parameters involved in mooring design, available from conducted research etc. and comparison with codes and guidelines. To demonstrate the effect of these parameters on strength through a case study. To study various phase during the life cycle of mooring from design to decommissioning and come up with a kind of a framework covering all important information.

1.3 Structure of the thesis

The thesis divided into seven chapter. Chapter 2 dealing with mooring system in general. Chapter 3 starting with design of mooring components, fabrication of mooring components and installation of the mooring line. Chapter 4 dealing with fatigue design and corrosion. Chapter 5 is about integrity management, inspection, monitoring and life extension. Chapter 6 is to design of mooring chain in ABAQUS (Case Study) and finally discussion and conclusion.in chapter seven.

2 Mooring System

2.1 Overview of Chapter

A brief overview of different possible mooring systems and mooring line components.

2.2 Mooring lines

2.2.1 Chain

There are primary two type chain constructions. Stud-link and stud-less. Chain is strong, reliable, and relatively easy to handle. Over the past stud-link chain has been used for mooring of MODUs and FPSO typically in shallow water. The stud provide stability to the link during handling of the chain link [1, 2]

Stud-less or open link chain have been used for permanent mooring systems. Removing the stud reduces the weight per unit of strength and increase the chain fatigue life, but in the other hand handling of chain link become difficult [1, 2].

Chain size is specified as the nominal diameter of the link and denoted by letter D. Properties of chain is an important component for mooring systems design. Depending on the nominal tensile strength of the steels used for manufacture, chains are divided into five grades as R3, R3S, R4, R4S and R5. Figure 2.1 shows the breaking strength of chain in different grades.

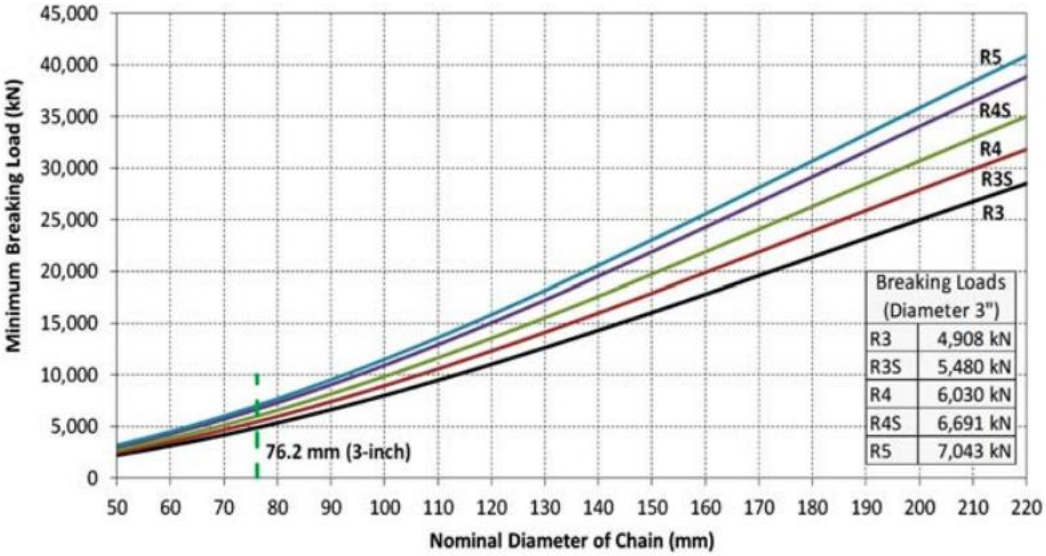


Figure 2.1. Breaking strength of chain in different grades [2]

2.2.2 Properties of chains

The definition of the chain dimensions is given in the figure 2.2. in the figure the number without brackets concern the dimensions of a stud-less chain, while the numbers between brackets and in italic give the dimensions of a stud-link chain [42].

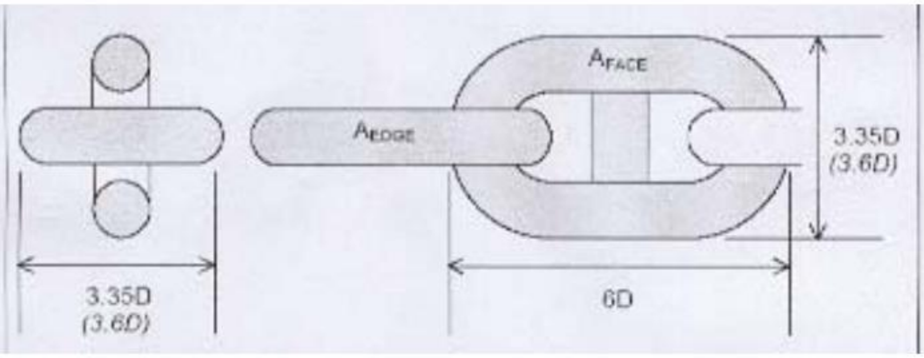
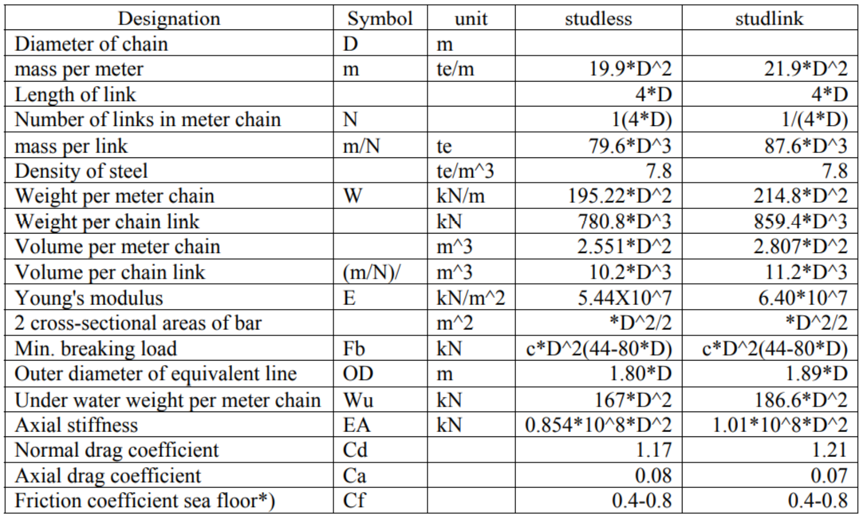


Figure 2.2. Dimension of chain [42]

Based on extrapolation and interpolation of available diameters the breaking strength, stiffness and the weight can be approximated as shows in Table 2.1 and the result tabulated in the Table 2.2 [42].



Designation	Symbol	unit	studless	studlink
Diameter of chain	D	m		
mass per meter	m	te/m	19.9*D^2	21.9*D^2
Length of link			4*D	4*D
Number of links in meter chain	N		1(4*D)	1/(4*D)
mass per link	m/N	te	79.6*D^3	87.6*D^3
Density of steel		te/m^3	7.8	7.8
Weight per meter chain	W	kN/m	195.22*D^2	214.8*D^2
Weight per chain link		kN	780.8*D^3	859.4*D^3
Volume per meter chain		m^3	2.551*D^2	2.807*D^2
Volume per chain link	(m/N)/	m^3	10.2*D^3	11.2*D^3
Young's modulus	E	kN/m^2	5.44X10^7	6.40*10^7
2 cross-sectional areas of bar		m^2	*D^2/2	*D^2/2
Min. breaking load	Fb	kN	c*D^2(44-80*D)	c*D^2(44-80*D)
Outer diameter of equivalent line	OD	m	1.80*D	1.89*D
Under water weight per meter chain	Wu	kN	167*D^2	186.6*D^2
Axial stiffness	EA	kN	0.854*10^8*D^2	1.01*10^8*D^2
Normal drag coefficient	Cd		1.17	1.21
Axial drag coefficient	Ca		0.08	0.07
Friction coefficient sea floor*)	Cf		0.4-0.8	0.4-0.8

Table 2.1. Properties of chain [42]

Friction coefficient are typically depended on seabed. According to [4, 12] friction coefficient sea floor recommends as 27.4 for RQ4 grade. The value for grade RQ3 is 21.1 according to [4, 12, 22]. According to [13] the value for grade 3 is set 19.6 and 13.7 for grade 2. The value for friction coefficient sea floor for grade R3 is give equal to 22.3 and for grade RS3 given as 24.9 [42].

Buried part of bottom chain (for line to suction anchor), main characteristics are:

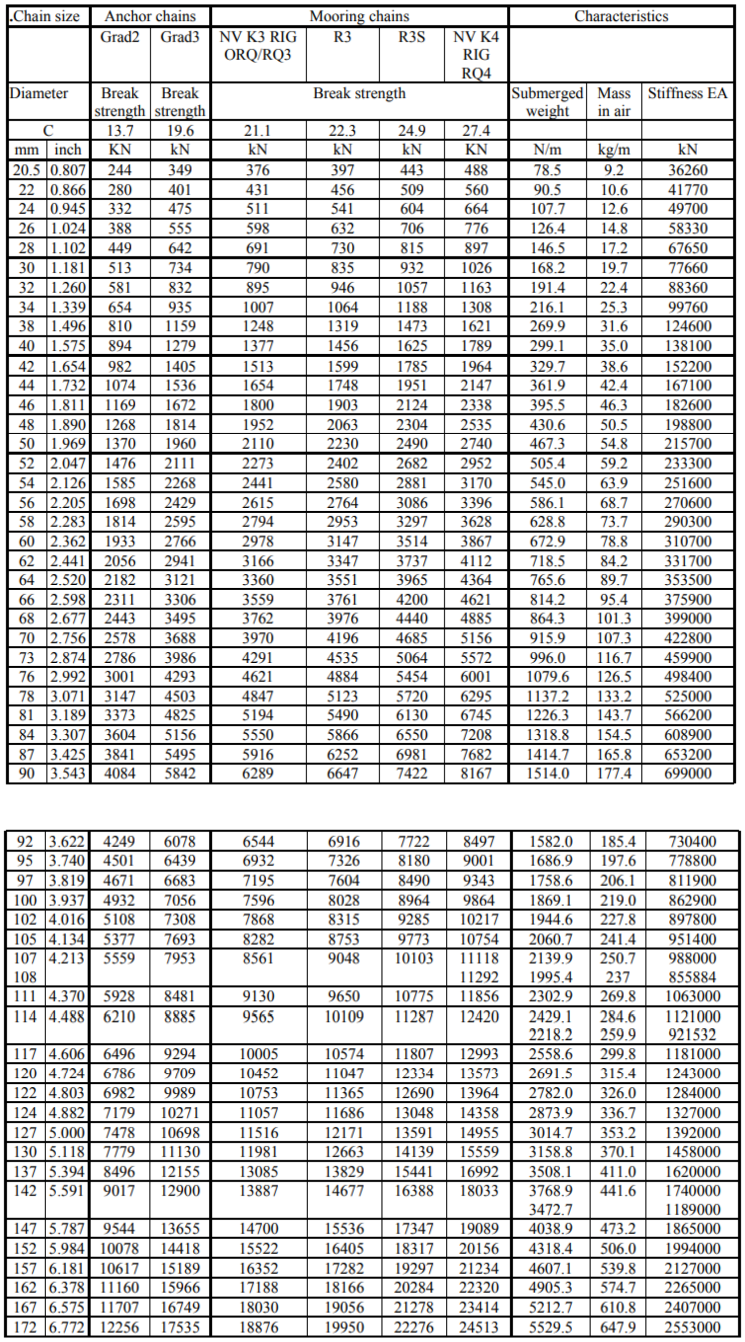
- Installed together with anchor
- Not inspectable, and hence more complicated to replace.
- Must be robust with respect to fatigue and corrosion.

Bottom chain main characteristics are:

- Sufficient length to prevent contact between fibre rope and seabed.
- Easy connection to pre-installation anchor ROV.
- Dimensions governed by ULS Load.
- Design lifetime may be an issue due to corrosion.

Top chain main characteristics are:

- Robust during installation and tensioning (wear and tear).
- Gives termination of fibre rope at reasonable depth, reducing risk of degradation by marine growth and UV light.
- Give tolerance for determining pre-constructed rope lengths with respect to uncertainties in bedding-in lengths and potential post-installation creep or shrinking.
- Easy to replace
- Corrosion and fatigue (OPB) are the governing effect for selection of dimension.



.Chain size		Anchor chains		Mooring chains				Characteristics		
		Grad2	Grad3	NV K3 RIG ORQ/RQ3	R3	R3S	NV K4 RIG RQ4			
Diameter		Break strength	Break strength	Break strength				Submerged weight	Mass in air	Stiffness EA
C		13.7	19.6	21.1	22.3	24.9	27.4			
mm	inch	KN	kN	kN	kN	kN	KN	N/m	kg/m	kN
20.5	0.807	244	349	376	397	443	488	78.5	9.2	36260
22	0.866	280	401	431	456	509	560	90.5	10.6	41770
24	0.945	332	475	511	541	604	664	107.7	12.6	49700
26	1.024	388	555	598	632	706	776	126.4	14.8	58330
28	1.102	449	642	691	730	815	897	146.5	17.2	67650
30	1.181	513	734	790	835	932	1026	168.2	19.7	77660
32	1.260	581	832	895	946	1057	1163	191.4	22.4	88360
34	1.339	654	935	1007	1064	1188	1308	216.1	25.3	99760
38	1.496	810	1159	1248	1319	1473	1621	269.9	31.6	124600
40	1.575	894	1279	1377	1456	1625	1789	299.1	35.0	138100
42	1.654	982	1405	1513	1599	1785	1964	329.7	38.6	152200
44	1.732	1074	1536	1654	1748	1951	2147	361.9	42.4	167100
46	1.811	1169	1672	1800	1903	2124	2338	395.5	46.3	182600
48	1.890	1268	1814	1952	2063	2304	2535	430.6	50.5	198800
50	1.969	1370	1960	2110	2230	2490	2740	467.3	54.8	215700
52	2.047	1476	2111	2273	2402	2682	2952	505.4	59.2	233300
54	2.126	1585	2268	2441	2580	2881	3170	545.0	63.9	251600
56	2.205	1698	2429	2615	2764	3086	3396	586.1	68.7	270600
58	2.283	1814	2595	2794	2953	3297	3628	628.8	73.7	290300
60	2.362	1933	2766	2978	3147	3514	3867	672.9	78.8	310700
62	2.441	2056	2941	3166	3347	3737	4112	718.5	84.2	331700
64	2.520	2182	3121	3360	3551	3965	4364	765.6	89.7	353500
66	2.598	2311	3306	3559	3761	4200	4621	814.2	95.4	375900
68	2.677	2443	3495	3762	3976	4440	4885	864.3	101.3	399000
70	2.756	2578	3688	3970	4196	4685	5156	915.9	107.3	422800
73	2.874	2786	3986	4291	4535	5064	5572	996.0	116.7	459900
76	2.992	3001	4293	4621	4884	5454	6001	1079.6	126.5	498400
78	3.071	3147	4503	4847	5123	5720	6295	1137.2	133.2	525000
81	3.189	3373	4825	5194	5490	6130	6745	1226.3	143.7	566200
84	3.307	3604	5156	5550	5866	6550	7208	1318.8	154.5	608900
87	3.425	3841	5495	5916	6252	6981	7682	1414.7	165.8	653200
90	3.543	4084	5842	6289	6647	7422	8167	1514.0	177.4	699000
92	3.622	4249	6078	6544	6916	7722	8497	1582.0	185.4	730400
95	3.740	4501	6439	6932	7326	8180	9001	1686.9	197.6	778800
97	3.819	4671	6683	7195	7604	8490	9343	1758.6	206.1	811900
100	3.937	4932	7056	7596	8028	8964	9864	1869.1	219.0	862900
102	4.016	5108	7308	7868	8315	9285	10217	1944.6	227.8	897800
105	4.134	5377	7693	8282	8753	9773	10754	2060.7	241.4	951400
107 108	4.213	5559	7953	8561	9048	10103	11118 11292	2139.9 1995.4	250.7 237	988000 855884
111	4.370	5928	8481	9130	9650	10775	11856	2302.9	269.8	1063000
114	4.488	6210	8885	9565	10109	11287	12420	2429.1 2218.2	284.6 259.9	1121000 921532
117	4.606	6496	9294	10005	10574	11807	12993	2558.6	299.8	1181000
120	4.724	6786	9709	10452	11047	12334	13573	2691.5	315.4	1243000
122	4.803	6982	9989	10753	11365	12690	13964	2782.0	326.0	1284000
124	4.882	7179	10271	11057	11686	13048	14358	2873.9	336.7	1327000
127	5.000	7478	10698	11516	12171	13591	14955	3014.7	353.2	1392000
130	5.118	7779	11130	11981	12663	14139	15559	3158.8	370.1	1458000
137	5.394	8496	12155	13085	13829	15441	16992	3508.1	411.0	1620000
142	5.591	9017	12900	13887	14677	16388	18033	3768.9 3472.7	441.6	1740000 1189000
147	5.787	9544	13655	14700	15536	17347	19089	4038.9	473.2	1865000
152	5.984	10078	14418	15522	16405	18317	20156	4318.4	506.0	1994000
157	6.181	10617	15189	16352	17282	19297	21234	4607.1	539.8	2127000
162	6.378	11160	15966	17188	18166	20284	22320	4905.3	574.7	2265000
167	6.575	11707	16749	18030	19056	21278	23414	5212.7	610.8	2407000
172	6.772	12256	17535	18876	19950	22276	24513	5529.5	647.9	2553000

Table 2.2. Result of chain properties [42]

2.2.3 Wire rope

Wire rope consists of individual wires wound in helical pattern to form a strand. Multi-strand or single-strand construction are used in offshore mooring, shown in figure 2.3. Multi-strand consists of 12, 24, 37, or more wire per strand. Multi-strand contains fiber or metallic. Independent wire rope core (IWRC) and wire-strand core (WSC) are two types of metallic core. IWRC is the most common core filling for heavy marine application [1, 2].

Two constructions of wire rope are used for permanent mooring, six-strand, and spiral-strand construction. Six-strand construction is typically used in applications with short design lives less than 8 or 10 years. While spiral strand construction is designed to be used in application from 10 to 30 years, depending on the level of corrosion protection. Six-strand wire is traditionally used due its low elastic stiffness, cost, and ease of handling. The disadvantages are low service life, the individual wires are galvanized, providing corrosion protection for about 8 years and due to its construction, it rotates under load. This construction-induced rotation can induce permanent twist into anchor leg system, and changes in tension can induce cycles of rotation, resulting in torsional loading of the chain that could result in undesired stresses and reduction of the estimated fatigue life. [1, 2].

Spiral-strand wire is supplied either unsheathed or sheathed with a service life ranging from 10 to 30 years, respectively. Unsheathed spiral-stand wire requires care during installation. Re-spooling the wire rope from a shipping reel onto an installation reel, deploying it over s stern roller, or using grippers to support the wire during deployment can cause result-in loose wires at the socket. In addition, careful handling of the socket during installation is important [1, 2].

Single-strand ropes are more common in large permanent installation. The wires are wound as a helix with each layer wrapped in a different direction. This provides torque balancing, preventing the rope from twisting when under load. The spiral strand is more fatigue resistant than the multi-strand rope. Corrosion resistance is enhanced by either sheathing with a polyurethane coating, adding zinc filler wires, or using galvanized wires [1, 2].

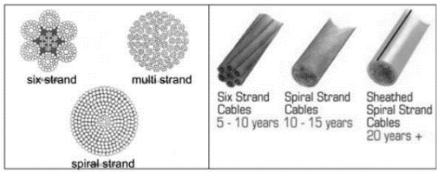


Figure 2.3. Wire rope construction [1]

2.2.4 Polyester rope

Polyester has now been used in permanent mooring systems and has been an enabling technology for extending mooring design to ultra-deep water. polyester, as a material and mooring component, has been studies extensively by the industry and all major societies. There have been issued various design guideline and detailed manufacturing and testing procedures to ensure suitability for offshore mooring. Polyester has developed an excellent track record for long-term performance, other than for its susceptibility to damage by contact with sharp or abrasive and objective. This requires well-defined installation equipment and procedure.

Polyester rope has light weight and high elasticity. Its high elasticity allows the use of taut mooring system in deep and ultradeep water without need for catenary compliance to limit dynamic tensions. Figure 2.4 shown the polyester rope construction.

Polyester four advantages are [1, 2]]:

- Reduced vessel offset
- Smaller mooring footprint
- Improved vessel payload capacity
- Excellent fatigue properties

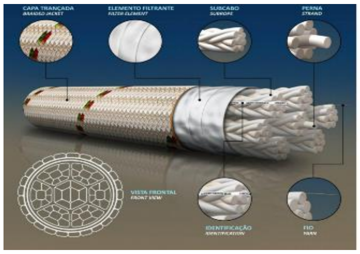


Figure 2.4. Polyester rope construction [5]

2.3 Anchors

Anchors are a critical component of offshore mooring systems. Suction forces and relying on self-weight anchors are types used for mooring systems. The common anchors types are used for offshore deep-water mooring are shown in figure 2.5.

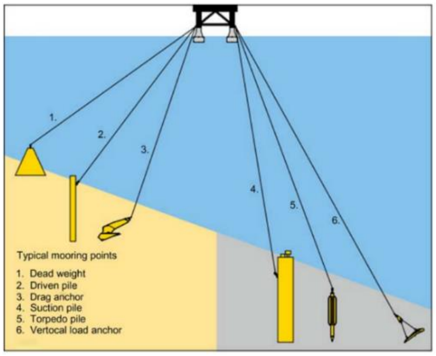


Figure 2.5. Different anchor types [6]

2.3.1 Drag embedment anchors

A DEAs is a bearing plate known as the fluke, inserted into the seabed by dragging it with wire rope or chain. In stiff clays and sand, the fluke-shank angle is typically set around 30 degrees and around 50 degrees for soft clay. The new generation of the anchor has high holding capacity in soft soil conditions [1, 2]. Figure 2.6 shown the construction of the DEA.

Figure 2.6. Construction of DEA [6]

Among the simplest drag anchor capacity prediction methods are charts which provide estimate of holding capacity, drag distance and penetration depth as function of anchor weight for a range of soil types. These charts are usually anchor specific based on full-scale or model testing and field experience. The important factor is fluke area which is correlated with anchor weight.

2.3.2 Vertical loaded anchors

VLA are suitable for anchoring in soft clay. The holding capacity of a VLA are depend on its final orientation and depth below the seabed. Figure 2.7 shown construction of VLA.

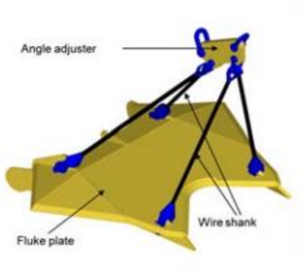


Figure 2.7. Construction of VLA [6]

2.3.3 Suction anchors

Suction piles are cylindrical anchors with a large diameter as shown in figure 2.8. They are installed partially by self-weight penetration, with penetration to full installation depth accomplished by the application of suction.

Suction piles are normally designed with relatively thin walls. Different internal plate stiffeners and ring stiffeners are required for preventing structural buckling during installation and structural failure during operation. This type of anchor has been used for vertical loading e.g., TLP, but mostly used for catenary and taut mooring systems [1, 2].

Figure 2.8. Construction of suction piles [8]

Holding capacity of suction can be achieved by three type of analysis [2]. Limit equilibrium or plastic limit analysis methods, semiempirical methods and Finite Element Analysis (FEA) are these types. For deep-water permanent mooring, the design focus on the ultimate capacity of suction pile and not on the load deflection behavior.

2.3.4 Fairlead and stopper

Mooring lines are subjected to high wear rates and stresses at the fairlead and stopper arrangements. The long-term service of a mooring system requires that fairlead and stopper arrangements be designed to minimize wear and fatigue. For example, fairlead should provide sufficient sheave-to-rope diameter ration (i.e., D/d ratio) to minimize tension-bending fatigue on wire ropes. For chain, seven to nine pocket wildcat sheaves are typically used. Mooring chain is often stopped off at the vessel's hull to take direct mooring loads off the winch. Chain stopper and wire rope gripe are designed such that the stress concentration and wear within the chain or wire rope are kept at acceptable levels [1,2, 20]. Figure 2.9 shows chain stopper.

Figure 2.9. [9]

2.3.5 Connector

Different types of connectors have been used connecting adjacent mooring line segments, such as shackles, kenter links, pear links, C-links, and other others. Many of them have stress concentration point in their geometries, and therefore allowed to be used only in temporary mooring systems due to limited fatigue lives. For permanent mooring systems, D-shackles and H-links are two types commonly used to make connection between mooring line segments. Because inspection and replacement of connectors in a permanent mooring are difficult, their design need to be robust with adequate fracture toughness, fatigue, and corrosion protection. Manufacturing of connecting hardware should be subject to an appropriate level of quality assurance corresponding to the same quality as offshore mooring chain [1, 2, 20].

2.3.5.1 Connectors for permanent moorings

D-shackles is a connector that is very common in the offshore industry. It consists of a bow, which is closed by a pin. Many different types or shackles are available, depending on the application. The shackle can be used both temporary and permanent moorings, figure 2.10 shows a D-shackle being forged.

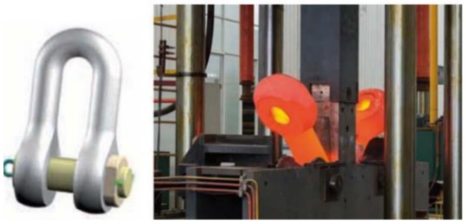


Figure 2.10. D-shackle is being forged [16]

H-link name after their shape and serve to connect two lengths of mooring line whether it is chain to chain, chain to wire rope, chain to polyester rope, or polyester rope to polyester rope. This type of connector was introduced to avoid time-consuming handling that is associated with D-shackles and allows for mooring line segment with different sizes to be easily connected to one anchor. Figure 2.11 shows an H-link connecting a chain segment to a polyester rope segment [2].

Figure 2.11. H-shackle connecting polyester rope and chain [16]

2.4 Catenary mooring line

In a spread mooring system, several pre-tensioned anchors lines are arrayed around the offshore floating unit to hold it in the desire location. The normal case is that the anchors, can be easily moved. This implies that the anchor in operation cannot be loaded by to large vertical forces, and to ensure that a significant part of the anchor lines lie on the seabed.

To achieve the greater stiffness and lighter anchor lines, offshore mooring cable should consist of heavy segment in the bottom part and light segment close to the water surface. The tension forces in the mooring cables, which are the means of applying restraining forces on the offshore floating unit, are due to the cable weight and or its elastic properties, depending on the manner in which the cable systems is laid [1, 2].

The initial tension, or pre-tension in a cable is often established using winches on the vessel or floating offshore unit. Figure 2.12 shows a catenary mooring line deployed from point A on the submerged hull of floating vessel to anchor at point B on the seabed.

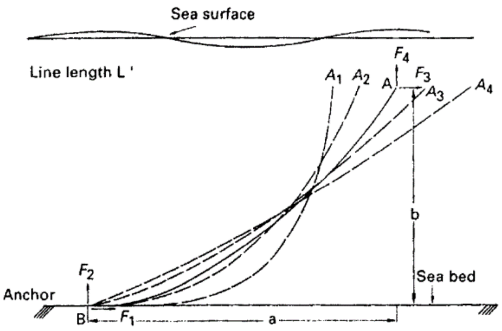


Figure 2.12. Behavior of mooring line [1]

The horizontal length a, is usually 5-20 times larger than the vertical length b. When the vessel (rig) is moved, the mooring line will be stretched up or sagged down. Touch down point will move, and we may get a vertical force in the part of mooring line lying on the seafloor. We do not want any vertical force on the anchor [1].

From a static point of view, the cable tension in the point A is due to total weight of the suspended line length in sea water. The behavior of catenary mooring line can be described by the catenary equation that can be used to derive line tensions and shape for any single line of mooring pattern. The equation is developed using mooring line as shown in figure 2.13 [1].

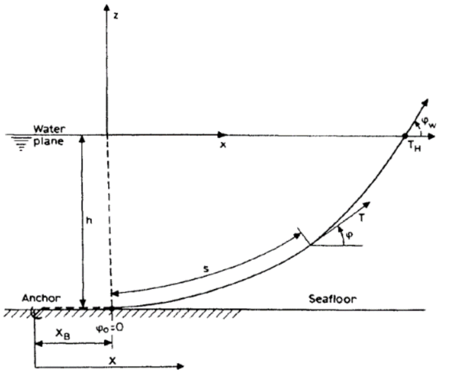


Figure 2.13. Catenary mooring line [1]

where,

T = Tension in the mooring line

T_H..=..Horizontal component of tension

h…= Water depth

X_B..=..Length from anchor to touch down point

A single line element is shown in figure2.14. The term w represents the constant submerged weight of hanging mooring line, T is line tension, A the cross-section area and E the elastic modulus. The mean hydrostatic force on the element are given by D and F per unit length.

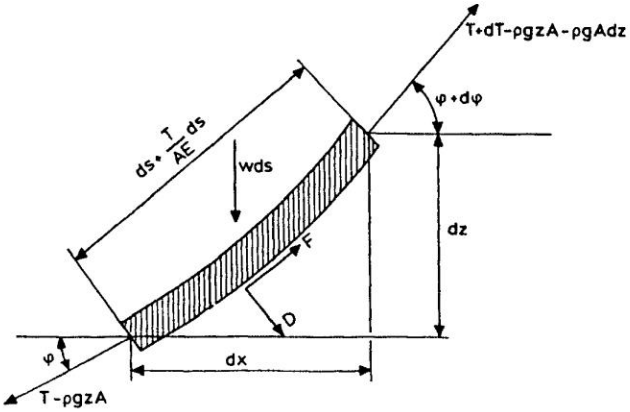


Figure 2.14. Force acting on an element on anchor line [1]

Inspecting the small element part and considering in-line and transvers forcing gives:

$$dT - \rho gAdz = \left[w \sin\phi = F\left(\frac{T}{EA}\right)\right] ds \qquad (2.1)$$

$$Td\phi - \rho gAzd\phi = \left[w \cos\phi + D\left(1 + \frac{T}{EA}\right)\right] ds \qquad (2.2)$$

Ignoring force F and D together with elasticity allows simplification of the equation though it is noted that elastic stretch can be very important and needs to be considered when line becomes tight or for larger suspended line weight or deep water.

With the above assumption we can obtain the suspended line length s and vertical length h as:

$$s = \left(\frac{T_H}{w}\right) \sinh\left(\frac{wx}{T_H}\right) \qquad (2.3)$$

$$h = \left(\frac{T_H}{w}\right)\left[\cosh\left(\frac{wx}{T_H}\right) - 1\right] \tag{2.4}$$

giving the tension in the line at the top, written in terms of catenary length s and depth d as:

$$T = \frac{w(s^2+d^2)}{2d} \tag{2.5}$$

The vertical component of line tension at the top end becomes:

$$T_Z = ws \tag{2.6}$$

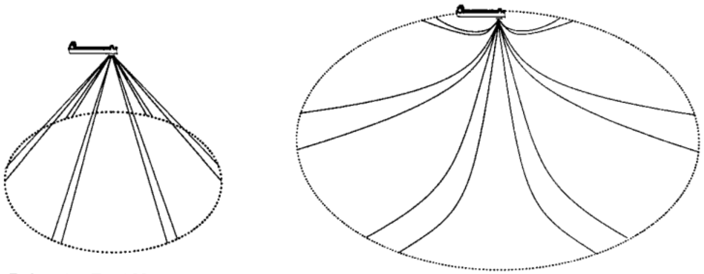
The horizontal component of tension is constant along the line and is given by:

$$T_H = T\cos\phi_w \tag{2.7}$$

It is noted that the above analysis assume that the line is horizontal at the lower end replicating the case where a gravity anchor with no uplift is used [1 2].

2.5 Taut mooring

The taut leg mooring is suitable for deep or ultradeep water. The taut leg mooring system has no line lying on the seabed in the static equilibrium position, and the mooring lines are taut from anchor to seabed to the fairlead on the floater. Therefore, the anchor footprint is smaller, and the mooring system use less line material compared to the catenary mooring systems. However, as the lines are taut the compliance to floater offset and dynamic response is mostly from line tensile stretch. Taut mooring systems are suitable for deep and ultradeep water application. Figure 2.15 shows taut leg mooring system with catenary one [1, 2].



Polyester Taut Mooring

Steel Catenary Mooring

Figure 2.15. Taut and catenary mooring systems [1]

3 Design, Fabrication, and Installation

3.1 Overview of chapter

A brief overview for different design methodology for permanents production facilities, and mobile offshore units. Offshore mooring design shall be performed based on the class society rules and industry standards.

3.2 Environmental loads

A floating structure in open water experience the environmental load caused by wind, wave, current and ice. The mooring system designed to withstand the environmental loads, such that the strength and fatigue requirements are met by all mooring components. The magnitude and direction of wind, waves and current are the most important parameters during the design of mooring systems, figure 3.1 shows the acting of these loads on the floating unit.

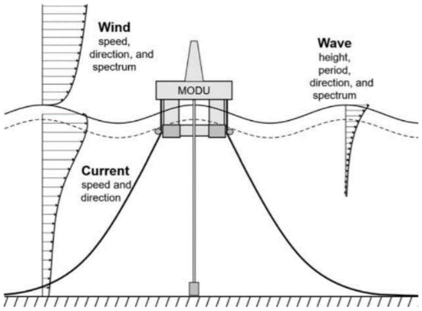


Figure 3.1. [2]

3.2.1 Loads in different frequency ranges

Environmental loads acting on the floating unit can be categorized according to distinct frequency bands:

- Steady loads
- Wave frequency cyclic loads
- Low frequency cyclic loads

Steady loads such as mean wind, current, and mean drift forces are constant in magnitude and direction for duration of interest. Steady loads push the floating unit to an offset that is counterbalanced by the mooring force. Wave frequency cyclic load with typical periods ranging from 5 to 30 second. The loads result in wave frequency motions of the floating vessel, which create cyclic tensions that contribute to maximum mooring line tensions and fatigue damage accumulation in the mooring lines. Low frequency cyclic loads that excite the entire floating system including its mooring system at natural periods in surge, sway and yaw with typical natural periods ranges from 3 to 10 minutes [1, 2].

3.2.2 Wind load

Wind imposes static and low-frequency dynamic loads on the floating structure. It also generates waves and current that add loads on the structure and mooring lines. Winds is typically defined as the direction from which the wind blows. The wind speed varies with time and height above the sea surface [3, 17]].

3.2.3 Wave load

Waves generate wave loads on the floater that include wave frequency dynamic loads and the slowly varying (low frequency) wave drift forces. There are two types of wave, wind wave and swell. Wind waves are surface wave that result from the wind blowing over an area of water surface. Swell is generated by global weather systems where wind blows for a duration of time over a fetch of water [2, 3, 17]].

3.2.4 Current load

Current generate loads on the floating structure and its mooring and riser systems. They are also generating vortex-induced motion (VIM) on the floaters with a deep-draft cylindrical hull such as Spar or a deep-draft columned hull such as a semisubmersible. Current typically defined by direction and velocity profile with depth [2, 3, 17]. According to DNV GL-OS-E301[3], the following environmental effects shall be considered:

- Waves
- Wind
- Current
- Marine growth
- Tide and storm surge
- Earthquake
- Temperature
- Snow and ice

The environmental effects to be applied in the mooring line response calculations for the ULS and ALS shall include the most unfavorable combination of wind, wave and current with a return period of no less than 100 years for the combination. Unfavorable conditions are those conditions leading to higher mooring loads. Both the intensities and the directions of environmental effects are significant [3].

3.2.5 Environmental conditions

The load effects are based on the predicted tension in the mooring lines, normally obtained by calculation. The analysis of the line tensions shall consider the motion of the floating unit induced by environmental loads, and response of the mooring lines too these motions. The characteristic load effects are obtained for stationary, environmental states. Each stationary environmental state may be specified in terms of [3]:

- Significant wave height (H_S)
- Peak wave period (T_p)
- Wave spectrum (JONSWAP or double-peaked)
- Wave energy distribution
- Main wave direction
- Mean wind speed, over a 1 hour averaging period 10 m above sea level ($U_{1\ hour,10m}$)
- Wind spectrum function
- Wind direction
- Surface current speed (V_C)
- Current profile over depth
- Current direction

The same environmental conditions should be considered for the ULS and ALS, while a wider range of environmental conditions must be considered for the FLS.

3.3 Design basis

The design basis, also known as design premise, contains all the essential information and requirements. An outline of a sample design basis is given below [1, 2]:

- Mooring system design information
    - Location and water depth
    - Vessel geometry and loading condition
    - Metocean condition and design load cases
    - Risers, umbilicals and flowline information
    - Design analysis software to be used
- Mooring system design constraints
    - Layout of subsea infrastructure such as pipelines
    - Map of seabed hazard such as sensitive marine habitats
- Mooring system design criteria
    - Design life
    - Design standard
    - Vessel offset limit
    - Strength criteria
    - Fatigue criteria
    - Corrosion allowance
    - Anchor design requirement
- Deliverables

Following are the summarized mooring design procedures [2]:

- To maintain the floating structure on station within specified tolerance under normal operating and extreme storm conditions, and the excursion of the floater must be kept within the limit without overstretching the riser and umbilicals.
- To provide mooring system with sufficient strength and fatigue life to guarantee the operability and reliability of the offshore systems.

3.4 Design process

Mooring system design involves the following the following process [2]:

- Type of mooring system
- Mooring profile
- Mooring pattern
- Mooring line composition
- Type of anchor
- Onboard equipment

3.4.1 Design the mooring pattern

The selection of a mooring system configuration is typically done by varying the parameters until a cost-effective system is found that complies with regulatory and functional requirements. Following are the key steps in the design proses [2]:

- Determine anchor radius (i.e., anchor distance)- For a deep-water taut leg system, a good starting point for line length is to have a R/D ratio at 1.4, that is anchor radius is 1.4 times the water depth.
- Determine number (and size) of lines- This step consists simply of performing a qualified estimate of how many lines will provide a cost-effective mooring system. As general rule, the number of lines should be kept to a minimum as this is likely to be the most cost-effective design due to fewer fairleads/winches and less installation time.

  This step also determines the minimum line size for the given number of mooring lines. Pretensions of the lines are also checked to ensure they stay roughly between 10% and 20% of the minimum breaking load (MBL).

  Mooring patterns with fewer lines, such 4 x 2 are normally governed by the safety factor for damaged condition. With more lines, the mooring design are then governed by the safety factor for intact condition and redundancy check may become trivial. Figure 3.2 shows mooring patterns with different number and sizes for semisubmersible.

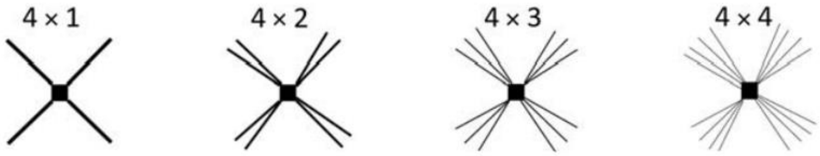


Figure 3.2. Various mooring pattern for semisubmersible [2]

- Determine grouping and spread angles- This step starts by identifying if there are constraints on the mooring pattern, for example larger riser corridors or nearby floating/subsea infrastructures.
  A floating production system can have either a spread or a grouped (clustered) mooring pattern as show the in the figure 3.3. The spread mooring systems in this context means that the angles between all lines are similar, so they are also called evenly spread mooring.
  Grouped mooring systems have three or four groups with tightly spaced lines in clusters. They are also called cluster mooring.
  For semisubmersibles, the grouping will have to consist of for groups, while spars can have three or four groups. Generally, for a system with large number of mooring line (more than nine) grouped systems are preferred to allow more open space for the riser as shown in figure 3.3, and better sharing of loads. For grouped systems, the spread angle between adjacent lines is typically 3-5 degree.

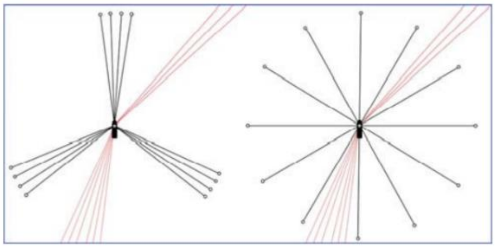


Figure 3.3. Grouped versus evenly spread mooring pattern [2]

3.4.2 Design the line composition

A mooring leg include several off-vessel components and on-vessel hard-ware that typically include the following from top to bottom [1, 2]:

- Mooring winches, chain jacks, chain stoppers
- Fairleads
- Chain, steel wire ropes or polyester ropes
- Connectors (H-links, tri-plate, shackles, etc.)
- Buoys or clump weight
- Anchors

From the design point of view, choosing the line materials depends on the characteristics of the components, particularly the specific weight in seawater. In general, chain is very heavy and costly but highly resistance to handling and abrasion. For permanent mooring systems, chain is typically used for the top segment in the line composition. This is because the top chain is locked securely by the chain stopper and stay there for years [1, 2].

Special consideration must be given to the top chain length including [2]:

- Length between the fairlead and first connector, minimum allowance at 10-15m for chain repositioning.
- Extra length to accommodate polyester rope elongation
- Extra length to account for the tolerance of anchor location
- Extra length to back-fill the segment of a polyester test insert, if applicable
- Extra length to allow the vessel to move an offset for drilling operation if applicable

Wire rope is less heavy than chain, and reasonably resistant to handling, so it is often used for the suspend portion of the mooring profile. Wire rope is not recommended to be placed at the touchdown point because it can suffer from excessive bending [1, 2].

Polyester rope is typically used in deep-water moorings to reduce the mooring’s self-weight and to absorb the line stretch under vessel motion. Polyester rope is only used for the suspended portion in the mooring line composition [1, 2].

Polyester and wire rope segments should in general, not touch the seabed in any normal or extreme conditions. Polyester ropes also need to stay submerged and maintain a clearance from the sea surface, say 100 to avoid any buildup of hard marine growth [1, 2].

Polyester ropes have the drawback of permanent elongation that comes from bedding-in and creep. Bedding-in of new ropes leads to an elongation of around 4%-6% of the rope length. The common practice is to remove as much as possible of the bedding-in elongation during installation by preloading (stretching) the line. Creep elongation generally is less than 1% of the rope length over the service life for a permanent mooring [1, 2].

3.5 Design consideration

There are at least four variables to be tuned during the design process to develop an optimum mooring configuration that conforms to industry standards and class rules. These includes vessel offset, line tension, fatigue damage and clash avoidance [1, 2].

3.5.1 Limiting vessel offset

Risers and umbilicals impose a limitation on the allowable vessel offset. In shallow water, the ratio of floater extreme offset to water depth is much larger and the risers/umbilicals are more likely to be overstretched. Therefore, the floater must be kept in a smaller excursion radius [2].

In deep water, risers/umbilicals feel less impact from the same offset and wave induced vessel motion. While the wave-frequency motion is independent to mooring system, the vessel static offset and slow drift (i.e., low-frequency) motion depend on many factors such as line profile, pretension, line material, mooring line spread, etc. In general, a taut leg profile tends to control the vessel offset better. Line material of high tensile stiffness can also reduce vessel offset. The possible means to reduce vessel offset include [2]:

- Choose taut leg profile in deep water
- Increase line tension
- Use more mooring line
- Use lightweight material to minimize the catenary effect.
- Use clump weight or heavy chain at the touch down zone.
- Arrange line spread in the direction of extreme environment

3.5.2 Minimizing line tension

The mooring line tension can be predicted by mooring analysis and if necessary, verified by model test. The mooring tension is kept withing the design limit, which is 60% and 80% of MBL for intact and damage conditions, respectively as required by most codes. Tension in mooting line can potentially cause various kinds of integrity issues, such as interlink wear and metal fatigue. The possible means to minimize the line tension include [2]:

- Select the most suitable mooring profile for water depth
- Use more mooring lines
- Choose optimum line spread according to environment directionality
- Choose lighter and less-stiff line material such as polyester
- Use complaint mooring leg configuration

3.5.3 Reducing fatigue damage accumulation

The field life is an important design parameter. The mooring system must have adequate fatigue life that exceeds the field life including fatigue safety factor. The chain is most vulnerable to fatigue failure. The possible means to improve the fatigue life include [2]:

- Reduce dynamic tension which can be done by improving the hull design so that the vessel motion and vortex-induced motion (VIM) are reduced
- Adopt a better design for fairlead- out-of-plane bending fatigue can be mitigated by fairleads with dual articulation (double axis), low-friction bearing, and/or longer hawse pipe.

3.6 Design criteria

According to DNV-OS-E301 [3], all mooring system shall be analyzed according to design criteria formulated in terms of three limit state equations:

- An ultimate limit state (ULS) to ensure that the individual mooring lines have adequate strength to withstand the load effects imposed extreme environmental actions.
- An accidental limit state (ALS) to ensure that the mooring system has adequate capacity to withstand the failure of one mooring line, failure of one thruster or one failure in the thruster's control or power systems may cause that several thrusters not working.
- A fatigue limit state (FLS) to ensure that the individual mooring lines have adequate capacity to withstand cyclic loading.

Each limit state is formulated as design equations or inequality in the form [3]:

$$Design\ capacity - Design\ load\ effect\ \geq 0$$

where,

$$Design\ capacity\ = \frac{characteristic\ capacity}{partial\ safety\ factor\ on\ capacity}$$

$$Design\ load\ effect\ = characteristic\ load\ effect \cdot partial\ safety\ on\ load\ effect$$

The effective elastic modulus shall be obtained from the manufacturer of the mooring line component. According to DNV-OS-E301 [3], for preliminary design the effective elastic modulus applied in the mooring analysis may be taken as:

Stud chain R3/R4/R5: not less than $5.6 \cdot 10^{10}\,\frac{N}{m^2}$

Stud less chain R3: $(5.40 - 0.0040 \cdot d) \cdot 10^{10}\,\frac{N}{m^2}$

Stud less chain R4: $(5.45 - 0.0025 \cdot d) \cdot 10^{10}\,\frac{N}{m^2}$

Stud less chain R5: $(6.00 - 0.0033 \cdot d) \cdot 10^{10}\,\frac{N}{m^2}$

where,

d = is the chain nominal diameter in mm. Vicinay has provided the elastic modulus for stud less chain.

Stranded rope:

$7.0 \cdot 10^{10} \frac{N}{m^2}$ corresponding to nominal diameter of the steel wire rope

Spiral rope:

$1.13 \cdot 10^{11} \frac{N}{m^2}$ corresponding to nominal diameter of the steel wire rope.

According to DNV-OS-E302 [4], the following statistic are required for the strength of the components that make up the main body of the mooring line:

μ_s = the mean value of the breaking strength of the component.

δ_s = the coefficient of variation of the breaking strength of the component.

Then the characteristic strength of the body of the mooring line constructed from this component is defined by:

$$S_c = \mu_s[1 - \delta_s(3 - 6\delta_s)] , \qquad \delta_s < 0.10 \tag{3.1}$$

This formulation is applicable for components consisting of chain, steel wire rope and synthetic fibre rope.

When statistic of the breaking strength of a component are not available, the characteristic strength may be obtained from the minimum breaking strength S_{mbs} of new component as:

$$S_C = 0.95\, S_{mbs} \tag{3.2}$$

For steel wire rope going over fairleads, the S_C shall be reduced by:

$$E_B = 1 - \frac{0.5}{\sqrt{\frac{D}{d}}} \tag{3.3}$$

where,

D = Fairlead diameter

d = wire rope diameter

When the strength distribution is based on test statistic, the statistical uncertainty in the results depend on the number of tests performed. A simple expression has been fitted to these results, and the reduced characteristic strength S_C^* is be expressed as:

$$S_C^* = S_c\left[1 - 2.0\left(\frac{\delta_s}{n}\right)\right] \tag{3.4}$$

where,

δ_s = is the coefficient of variation of the breaking strength of the component.

n = is the number of tests, not less than 5.

According to DNV -OS-E301[3], two consequence classes are introduced in the ULS and ALS defined as:

Class 1: where mooring system failure is unlikely to lead to unacceptable consequences, such as loss of life, collision with an adjacent platform, uncontrolled outflow of oil or gas, capsize or sinking.

Class 2: where mooring system failure may well lead to unacceptable consequence of these types.

The design equation for the ULS is given by:

$$S_C - T_{C-mean} \cdot \gamma_{mean} - T_{C-dyn} \cdot \gamma_{dyn} \geq 0 \tag{3.5}$$

where,

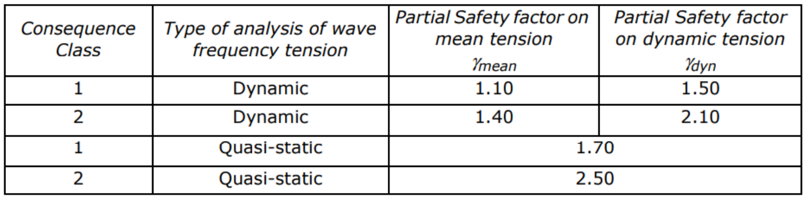
T_{C-mean} = is the characteristic mean line tension, due to pretension and mean environmental loads. The mean environmental loads are caused by static wind, current and mean wave drift forces.

T_{C-dyn} = is the characteristic dynamic line tension induced by low-frequency and wave-frequency motions.

The design equation may conveniently be reformulated by introducing a utilization factor, u:

$$u = \frac{S_C - T_{C-mean} \cdot \gamma_{mean} + T_{C-dyn} \cdot \gamma_{dyn}}{S_C} \text{ , } where \;\; u \leq 1 \qquad (3.6)$$

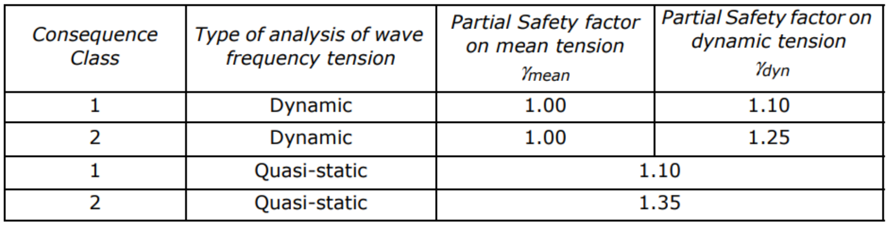
Table 3.1 given the partial safety factors for ULS.



Consequence Class	*Type of analysis of wave frequency tension*	*Partial Safety factor on mean tension* γ_{mean}	*Partial Safety factor on dynamic tension* γ_{dyn}
1	Dynamic	1.10	1.50
2	Dynamic	1.40	2.10
1	Quasi-static	1.70	
2	Quasi-static	2.50	

Table 3.1. Partial safety factors for ULS [3]

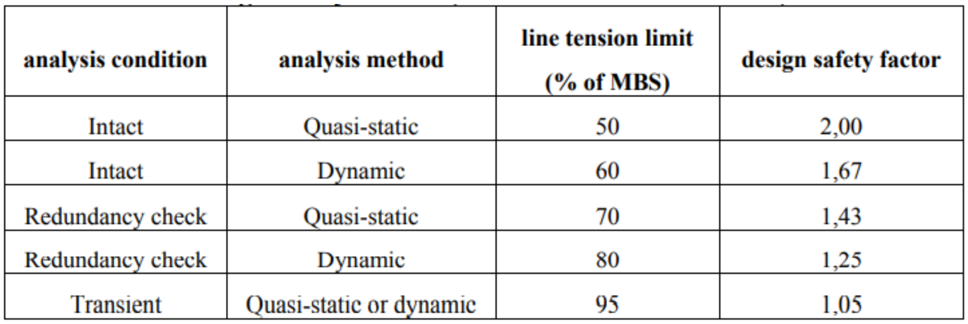
The design equation for the ALS limit state is identical to the ULS limit state, but the partial safety factor is given in table 3.2. The combination of an accidental line failure with characteristic loads based on a 100-year return period is relatively conservative. Hence, the partial safety factors in the table 3.2 are relatively small, i.e. close to unity. These factors should be adequate even the loading is dominated by the mean tension, if 100-year environmental conditions give rise to a significant portion of the mean tension [3].



Consequence Class	*Type of analysis of wave frequency tension*	*Partial Safety factor on mean tension* γ_{mean}	*Partial Safety factor on dynamic tension* γ_{dyn}
1	Dynamic	1.00	1.10
2	Dynamic	1.00	1.25
1	Quasi-static	1.10	
2	Quasi-static	1.35	

Table 3.2. Partial safety factors for ALS [3]

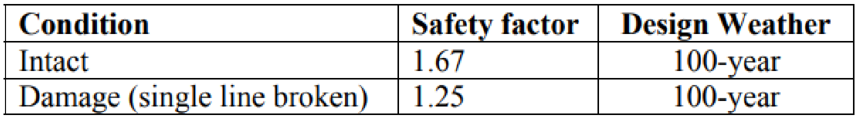
The design safety factor and line tension limits that shall be applied in the quasi-static or dynamic mooring analysis form ISO 19901-7 [42], tabulated in table 3.3.



analysis condition	analysis method	line tension limit (% of MBS)	design safety factor
Intact	Quasi-static	50	2,00
Intact	Dynamic	60	1,67
Redundancy check	Quasi-static	70	1,43
Redundancy check	Dynamic	80	1,25
Transient	Quasi-static or dynamic	95	1,05

Table 3.3: Safety factor [42]

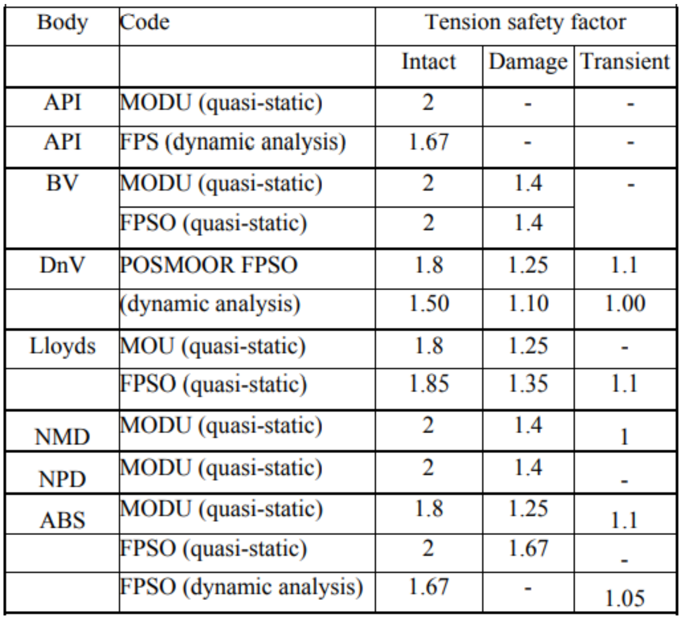
To confirm or compare the safety factors of the different societies for the loads in the mooring chain data are tabulated in table 3.4.[42].



Condition	Safety factor	Design Weather
Intact	1.67	100-year
Damage (single line broken)	1.25	100-year

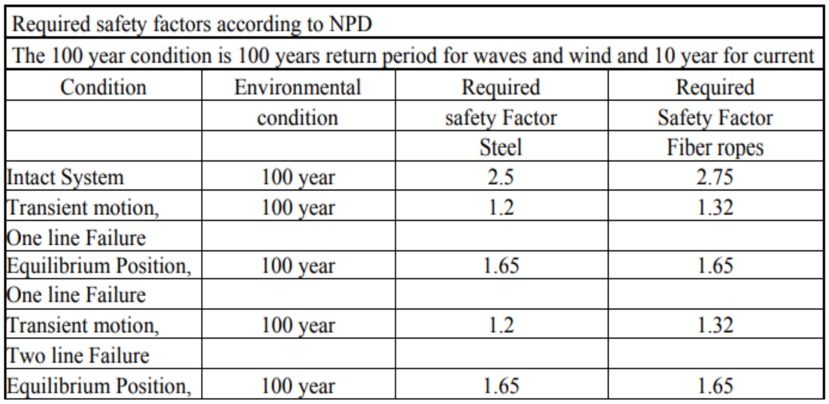
Table 3.4. Safety factor [42]

In the table 3.5 and 3.6 a comparison between different regulation and classification societies are represented.



Body	Code	Tension safety factor		
		Intact	Damage	Transient
API	MODU (quasi-static)	2	-	-
API	FPS (dynamic analysis)	1.67	-	-
BV	MODU (quasi-static)	2	1.4	-
	FPSO (quasi-static)	2	1.4	
DnV	POSMOOR FPSO	1.8	1.25	1.1
	(dynamic analysis)	1.50	1.10	1.00
Lloyds	MOU (quasi-static)	1.8	1.25	-
	FPSO (quasi-static)	1.85	1.35	1.1
NMD	MODU (quasi-static)	2	1.4	1
NPD	MODU (quasi-static)	2	1.4	-
ABS	MODU (quasi-static)	1.8	1.25	1.1
	FPSO (quasi-static)	2	1.67	-
	FPSO (dynamic analysis)	1.67	-	1.05

Table 3.5: Comparison of safety factors [42]

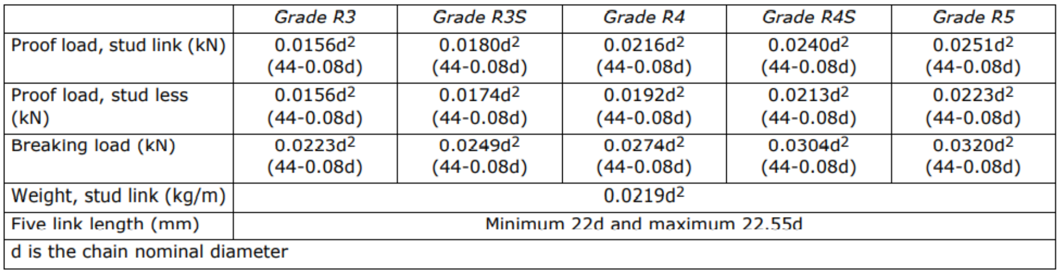


Required safety factors according to NPD			
The 100 year condition is 100 years return period for waves and wind and 10 year for current			
Condition	Environmental condition	Required safety Factor Steel	Required Safety Factor Fiber ropes
Intact System	100 year	2.5	2.75
Transient motion,	100 year	1.2	1.32
One line Failure			
Equilibrium Position,	100 year	1.65	1.65
One line Failure			
Transient motion,	100 year	1.2	1.32
Two line Failure			
Equilibrium Position,	100 year	1.65	1.65

Table 3.6: Comparison of safety factor [42]

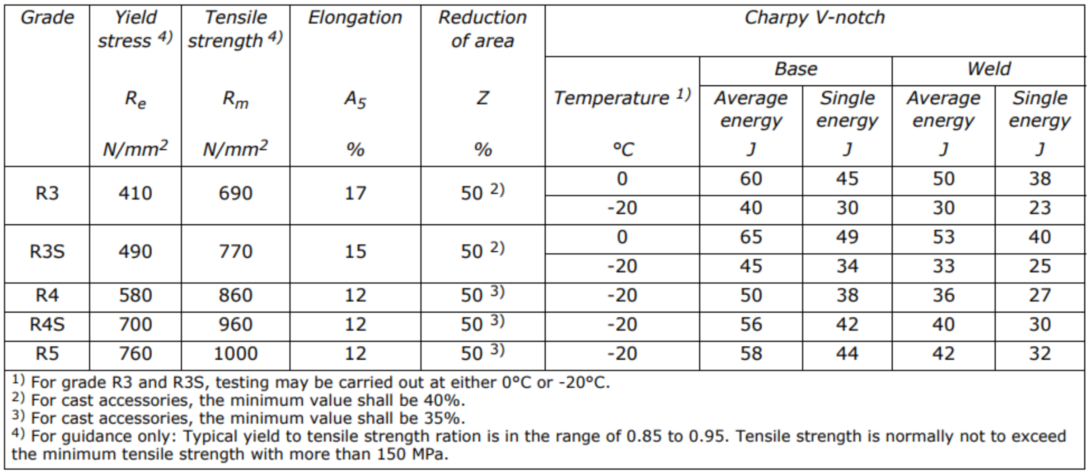
3.7 Capacity of chain

According to the Offshore Standard, DNVGL-0S-302 [4] each length of chain shall withstand the proof load specified in Table 3.7 without fracture and the minimum mechanical properties for different steel grades are specified in table 3.8.



	Grade R3	*Grade R3S*	*Grade R4*	*Grade R4S*	*Grade R5*
Proof load, stud link (kN)	$0.0156d^2 (44-0.08d)$	$0.0180d^2 (44-0.08d)$	$0.0216d^2 (44-0.08d)$	$0.0240d^2 (44-0.08d)$	$0.0251d^2 (44-0.08d)$
Proof load, stud less (kN)	$0.0156d^2 (44-0.08d)$	$0.0174d^2 (44-0.08d)$	$0.0192d^2 (44-0.08d)$	$0.0213d^2 (44-0.08d)$	$0.0223d^2 (44-0.08d)$
Breaking load (kN)	$0.0223d^2 (44-0.08d)$	$0.0249d^2 (44-0.08d)$	$0.0274d^2 (44-0.08d)$	$0.0304d^2 (44-0.08d)$	$0.0320d^2 (44-0.08d)$
Weight, stud link (kg/m)	$0.0219d^2$				
Five link length (mm)	Minimum 22d and maximum 22.55d				
d is the chain nominal diameter					

Table 3.7. Formulas for proof and breaking test loads, weight, and five link length. [4]



Grade	Yield stress [4)] R_e N/mm^2	Tensile strength [4)] R_m N/mm^2	Elongation A_5 %	Reduction of area Z %	Charpy V-notch				
						Base		Weld	
					Temperature 1) °C	Average energy J	Single energy J	Average energy J	Single energy J
R3	410	690	17	50 2)	0	60	45	50	38
					-20	40	30	30	23
R3S	490	770	15	50 2)	0	65	49	53	40
					-20	45	34	33	25
R4	580	860	12	50 3)	-20	50	38	36	27
R4S	700	960	12	50 3)	-20	56	42	40	30
R5	760	1000	12	50 3)	-20	58	44	42	32

1) For grade R3 and R3S, testing may be carried out at either 0°C or -20°C.
2) For cast accessories, the minimum value shall be 40%.
3) For cast accessories, the minimum value shall be 35%.
4) For guidance only: Typical yield to tensile strength ration is in the range of 0.85 to 0.95. Tensile strength is normally not to exceed the minimum tensile strength with more than 150 MPa.

Table 3.8. Minimum mechanical properties for chain cables. [4]

The effective elastic modulus shall be obtained from the manufacturer of the mooring line component. According to DNV-OS-E301 [3], for preliminary design the effective elastic modulus applied in the mooring analysis may be taken as:

Stud chain R3/R4/R5: not less than $5.6 \cdot 10^{10} \frac{N}{m^2}$

Stud less chain R3: $(5.40 - 0.0040 \cdot d) \cdot 10^{10} \frac{N}{m^2}$

Stud less chain R4: $(5.45 - 0.0025 \cdot d) \cdot 10^{10} \frac{N}{m^2}$

Stud less chain R5: $(6.00 - 0.0033 \cdot d) \cdot 10^{10} \frac{N}{m^2}$

where,

d = is the chain nominal diameter in mm. Vicinay has provided the elastic modulus for stud less chain.

$$E_{eff} = \frac{F \cdot L}{2A \cdot \Delta L} \tag{3.7}$$

where,

F = is axial load

A = is cross-sectional area

L = is length of the chain link

ΔL = is elongation of chain link

3.7.1 Areas of Maximum Stress in a Chain Link

Chain links are complex, statically indeterminate structure subjected to a combination of bending, shear and tension when loaded. Figure 3.4 shows an approximation of stress distribution in a loaded link.

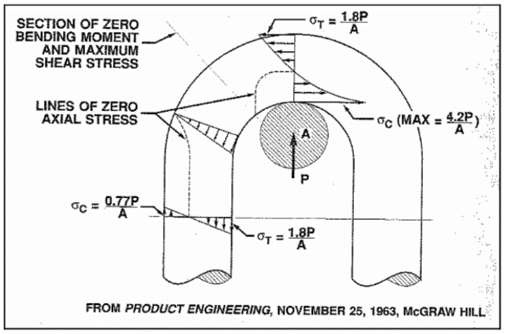


Figure 3.4. Approximation of the Stress Distribution in a Typical Chain Link [45]

3.7.2 Cross-sectional capacity

Eurocode 3, NS-EN 1993-1-1 [44], describes how to design the resistance of cross-sections of steel structure in the ultimate limit state (ULS). According to NS-EN 1993-1-1 [44], section 6.2.1, for the elastic verification the following yield criterion for a critical point of the cross-section may be used unless other interaction formulae apply:

$$\left(\frac{\sigma_{x,Ed}}{\frac{f_y}{\gamma_{M0}}}\right)^2 + \left(\frac{\sigma_{z,Ed}}{\frac{f_y}{\gamma_{M0}}}\right)^2 - \left(\frac{\sigma_{x,Ed}}{\frac{f_y}{\gamma_{M0}}}\right)\left(\frac{\sigma_{z,Ed}}{\frac{f_y}{\gamma_{M0}}}\right) + 3\left(\frac{\tau_{Ed}}{\frac{f_y}{\gamma_{M0}}}\right)^2 \leq 1 \qquad (3.8)$$

where,

$\sigma_{x,Ed}$ = is the design value of the longitudinal stress

$\sigma_{x,Ed}$ = is the design value of the transverse stress

τ_{Ed} = is the design value of the shear stress

γ_{M0} = is the partial safety factor

The above yield criterion can be conservative as it excludes the partial plastic stress distribution, which is permitted in elastic design. Therefore, it should only be performed where the interaction of based on resistances N_{Rd} ,M_{Rd} and V_{Rd} cannot be performed [44]. According to NS-EN 1993-1-1 [44], section 6.2.6 the design value of the shear may be obtained as follow:

$$\tau_{Ed} = \frac{V_{Ed}\, S}{I\, t} \tag{3.9}$$

where,

V_{Ed} = is the design value of the shear force

S = is the first moment of area about the centroidal axis of the portion of the cross-section between the point at which the shear is required and the boundary of the cross-section

I = is the second moment of area of the whole cross section

t = is the thickness at the examined point

According to NS-EN 1993-1-1 [44], the elastic cross-sectional capacities can obtain as follows:

$$M_{pl,Rd} = \frac{W_p\, f_y}{\gamma_{M0}} \tag{3.10}$$

$$V_{pl,Rd} = \frac{A_v\left(\frac{f_y}{\sqrt{3}}\right)}{\gamma_{M0}} \tag{3.11}$$

$$N_{pl,Rd} = \frac{A\, f_y}{\gamma_{M0}} \tag{3.12}$$

where,

$M_{pl,Rd}$ = is the design resistance for bending moment

$V_{pl,Rd}$ = is the design plastic shear resistance

$N_{pl,Rd}$ = is the design plastic resistance

W_p = is the plastic section modulus

A_v = is the shear area

Where an axial force is present, allowance should be made for its effect on the plastic moment resistance. According to NS-EN 1993-1-1, section 6.2.9.1 [44], for class 1 and class 2 cross section, the following criterion shall be satisfied:

$$M_{Ed} \leq M_{N.Rd} \tag{3.13}$$

where,

$M_{N.Rd}$ = is the design plastic moment reduced due to axial force N_{Ed}

For rectangular solid section without fastener holes $M_{N.Rd}$ should take as:

$$M_{N,Rd} = M_{pl,Rd}\left[1 - \left(\frac{N_{Ed}}{N_{pl,Rd}}\right)^2\right] \tag{3.15}$$

where,

N_{Ed} = is the design value of the axial force

$N_{pl,Rd}$ = is the plastic axial force capacity

According to NS-EN 1993-1-1 [44], section 6.2.10, where shear and axial force are present, allowance should be made for the effect of both shear force and axial force on the resistance moment. Where the design value of the shear force V_{Ed} exceed 50% of the $V_{pl,Rd}$ of the design resistance of the cross-section to combination of moment and axial force should be calculated using a reduced yield strength for the shear area as follows:

$$(1 - \rho)\, f_y \tag{3.16}$$

where,

$$\rho = \left(\frac{2\, V_{Ed}}{V_{pl,Rd}} - 1 \right)^2 \tag{3.17}$$

3.8 Fabrication

A brief overview of Offshore mooring components fabrication is described in this section.

3.8.1 Chain manufacturing

Certification of mooring chain component is required with ABS [12] and DNV GL-OS-E302 [4] considered the main references. The certification procedure includes recommend material, design, manufacture and testing requirements for offshore mooring chain and accessories. Chains are manufactured in a continuous process by flash butt welding (FBW) and heat treatment in a continuous furnace.

Tempering can alter strength easily for quenched and tempered steel [15]. Tempering temperature shall be not less than 560 °C and cooling after tempering shall be in water [4].

Manufacturing of chain begins with cutting of steel bars. Each bar is cut to required length. After the preheating, the bar goes to the bending machine, where it automatically bent and joined with previous link. Next step is flash butt-welding process, where two ends are welded with no material addition. After trimming step and stud inserting the chain undergo nondestructive testing, the welded chain then passes the heat treatment phase, which gives the material the final mechanical properties. Figure 3.5 shows manufacturing line for chain.

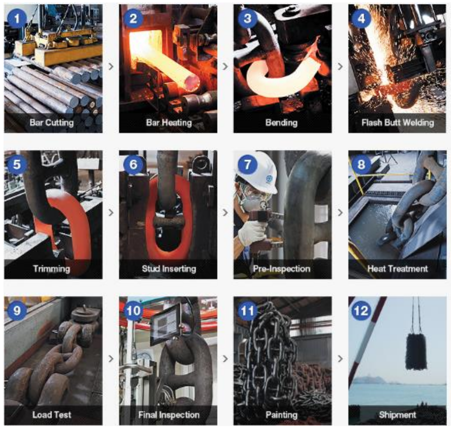


Figure 3.5. Manufacturing line of chain [14]

The next step chain proof loaded to test its resistance to tensile loads. After that chain is shot-blasted to prepare the surface for nondestructive inspection. Each link is inspected using fluorescent magnetic particles. In addition, its weld can be inspected using Phase Array Ultrasonic Testing (PAUT). PAUT is an effective method to fined defects in flash weld [2].

According to the Offshore Standard, DNVGL-0S-302 [4] each length of chain shall withstand the proof load specified in Table 3.7 without fracture and the minimum mechanical properties for different steel grades are specified in table 3.8.

The first step for manufacturing a stud-less chain is cutting steel bar to require length. Next step is heating the bars, using a convection furnace or electric heater. Once the temperature of each bar is adequate, the bar is washed using pressurized water to remove furnace scale. The wash bars are transported to the bender for two bending operations. After the first bend, the current end link of manufactured chain is inserted in the reaming straight part, and second bend closes the link, adding it to the chain as shown in figure 3.6a. The two end faces of the link are then joined by flash butt welding, figure 3.6b, burr is removed, and the link width is controlled. Every weld must be inspected to detect defects that could initiate fatigue failure and may be performed with difference ultrasonic modes. [8].

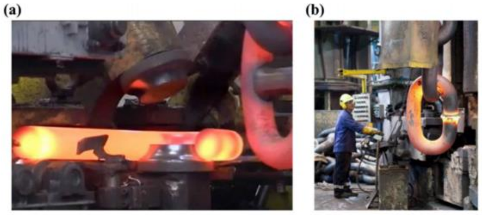


Figure 3.6. Stud-less chain manufacturing. [16]

Samples of the chain shall be subjected to mechanical testing after proof load testing. One tensile and nine Charpy V-notch test pieces shall be taken from each sample as shown in figure 3.7. the tensile tests piece and three impact test pieces shall be taken from the side of the link opposite the flash weld. Three impact test pieces shall be taken across the flash weld with the notch centered in the middle. The position of the weld shall be accurately identified by etching with a suitable reagent before cutting the notches. Their impact pieces shall be taken from the outer bend region. The longitudinal axis of the test pieces shall be one third radius below the surface [4].

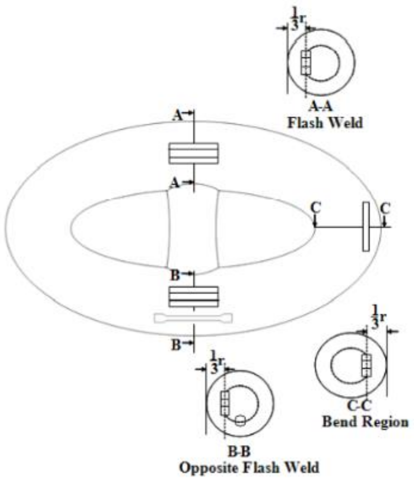


Figure 3.7. Position of test pieces. [4]

3.8.2 Polyester rope manufacturing

Synthetic ropes have many applications in the offshore industry including station keeping systems, offloading hawser, tails for vessel mooring line and installation adds [42].

Rope making is divided into several phase [20]:

- The fiber or filaments are prepared for twisting into yarns.
- The fiber or filaments are spun or bunched into yarns and yarns into cords for the manufacture of man-made filament ropes.
- Several yarns are twisted into strand.
- Several strands are twisted to rope.

For synthetic fibre ropes three basic constructions are used in different combinations depending on the requirement, figure 3.8 shows these are [42].

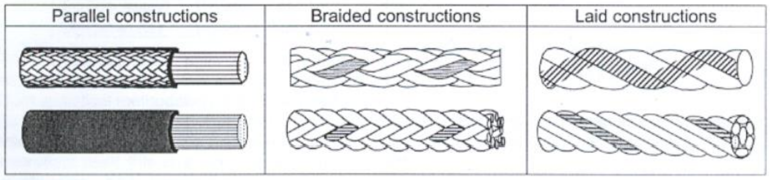


Figure 3.8. Construction of different synthetic rope [42]

Parallel strand keeps load-bearing yarns more aligned with the rope axis. The interaction between the fibers or strands will be low, and therefore it tends to get a higher strength [42].

Braided ropes, half the strands have a clockwise orientation and the other half have a counterclockwise orientation. The interaction between the strands is point contact. This gives a rotation-free rope will excellently handling characteristics [42].

For laid rope have all strand in one direction and have line contact between the strands. This provides excellent fatigue performance, both in tension and bending [42].

3.9 Installation

The installation of the mooring system can have an impact on the long-term performance of the mooring system. Especially ensuring that the mooring is installed in a manner that is consistent with the design basis. Accurate measurement of anchor leg component lengths, weight, and stiffness (as built) are very useful for installation purposes and final adjustment for the anchor leg system [1, 2, 20].

In addition, actual measurement of chain diameters and grip dimensions can provide a baseline for chain corrosion measurement. In shallow water mooring, fairlead angles measurement can be used to ensure proper pre-tension and load sharing, but in deep water mooring, fairlead angles are less sensitive and tension measurement may not be accurate [1, 2, 20].

In deep water moorings, monitoring vessel position and a well-defined point in the catenary say the shackle between top chain and wire can result in more accurate feedback on anchor leg configuration and load sharing between legs. The impact of installation on spiral strand wire rope construction is lower for sheathed wire other than damage to the sheathing, which can be avoided with proper equipment and procedure, than for unsheathed spiral stand wire rope. The allowable tension/bend radius ratio is more forgiving for sheathed rope and the vacuum extruded sheathing maintains the rope construction even if the rope twists. This should allow for a more robust mooring system once installed [1, 2, 20].

For systems with subsea connectors, it is important to ensure that the section of ground chain is connected to the pile is properly stored with the pile to ensure that once the connection is made the chain can be pulled away from the pile without twisting , as the twist may exist in the inverse catenary and not be visible [1, 2, 20]

Installation (pull in) wire ropes with streamlined closed spelter sockets can be hauled across fixed shoes during mooring leg installation. However, the wire rope’s outer strands need to be regular lay to reduce cutting into surface. Once the anchor leg system is installed and accepted in its as-installed configuration, a good as-built survey with quantitative measurements of floater position and specific location of shackles or other connectors for each anchor leg can provide aa good set of baseline measurements for the future monitoring and inspection of the system. In addition, good video of all connectors and terminations provide a good reference for future inspections [1, 2, 20].

3.9.1 Installation of permanent mooring

A typical mooring installation procedure for permanent floating production unit (FPU). The FPU has a hull shape of semisubmersible. It is moored by chain-polyester-chain system in deep water. Suction pile anchor is the most common anchor type for deep water FPUs and be used as an example to show the installation procedure [42].

A mooring installation can be divided into three phase that is [42]:

- Anchor installation-pile anchors are installed independently from the mooring lines.
- Mooring line pre-lay-all mooring lines are completely installed and laid down on the seabed.
- Hook-up to the FPU-the pre-laid mooring lines are picked up from the seabed and connected to the hull.

This approach allows the use of smaller vessel that are less expensive. It also reduces the complexity of the hook-up phase, as most of the connections between the line segments were already made during the pre-lay phase [42].

3.9.1.1 Installation of pile anchors

Suction anchors are normally transported offshore on a large anchor handling vessel (AHV) or on a separate barge. The anchors are either lifted by the crane as shown in figure 3.9 or launched by skidding from the transportation vessel and lowered to the sea floor.

Figure 3.9. Suction pile installation [2]

The crane stops lowering the anchor at a few meters above the seabed as shown in figure 3.10. A remotely operated vehicle (ROV) is used to monitor the anchor position and orientation to satisfy the allowable tolerance. The anchor penetrates under its own weight to an initial depth. After self-penetration is completed, an ROV pump is installed onto the anchor top as shown in figure 3.11. Further penetration to the final depth is accomplished by closing the evacuation valves and pumping seawater out of the anchor interior to create suction [1, 2].

The anchor orientation, inclination and penetration need to be continuously monitored, after achieved the required penetration depth, the suction pump is disconnected and the butterfly valve on the anchor top is shut. The installation of the suction anchor is complete [2].

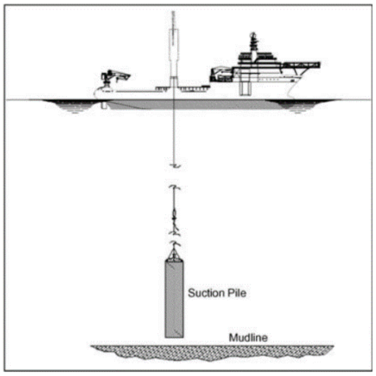


Figure 3.10. Suction pile is ready for self-penetration [2]

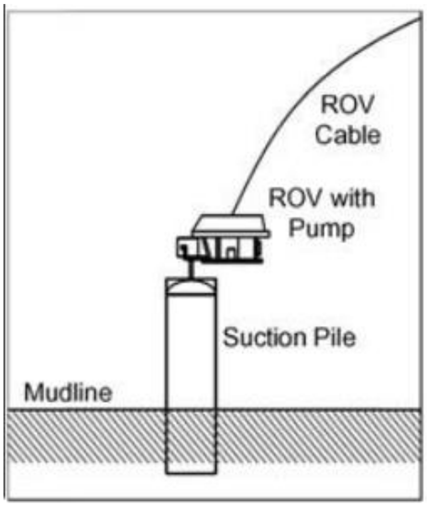


Figure 3.11 A remotely operation vehicle onto the anchor top [2]

Driven pile anchors are installed in a similar manner as suction pile anchor. They are lowered to the sea floor by a crane. The pile penetrates to an initial depth under its own weight. Penetration to final depth is accomplished by use of a pile hammer mounted on the pile tope. Alternatively, the pile can be drilled and grouted in place or the pile can be dropped from a calculated height above the sea floor using gravity to reach the design penetration depth [2].

3.9.1.2 Pre lay of mooring lines on seabed

Before starting on pre-laying, a line, an ROV survey is performed to search for obstruction that could interfere with the work along planned mooring line pre-lay routes and the anchor locations.

If the mooring line have polyester segments, the polyester ropes are spooled from its storage reel to one of the winch drum on the AHV. Once the polyester ropes are ready on the winch drum, the bottom chain segment can be over boarded and lowered. At the lower end of the bottom chain is a subsea connector as shown is figure 3.12 and figure 3.13, [2].

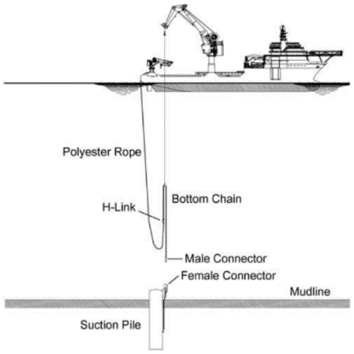


Figure 3.12. Lowering the bottom chain for connection to forerunner chain on the anchor pile [2]

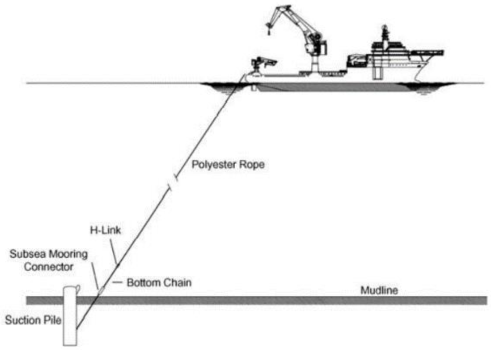


Figure 3.13: AHV is ready to pre-lay mooring line once bottom chain is connected to anchor's forerunner chain [2]

Mooring components are connected on the deck of the AHV as shown in figure 3.14 and deployed one by one according to the procedure. Polyester rope will follow the bottom chain and gets over boarded and deployed. Having paid out polyester rope segment, the lowering stops and the next rope segment is connected via a connector (e.g., H-link) [2].

Figure 3.14: Connecting polyester with the H-link to bottom chain [2]

When the male subsea connector eventually gets lowered to the top of the suction anchor, an ROV is used to connect the male to the female connectors. The female connector is temporarily seated on the top of the suction anchor and sealed with a cap that is removed by an ROV, prior to stabbing by the male subsea connector [2].

Once the bottom chain is connected to the forerunner chain the mooring line can be slowly paid out and laid on the seabed, while the AHV moves along the pre-lay route. The procedure is repeated for the rest of the mooring legs. The pre-lay operation is complete, and the mooring lines are we-parked on the seabed, waiting for the hook-up operation in the next phase [2].

Sheathed wire ropes can be wet parked if they are carefully laid to avoid bending and compression. They are typically pre-laid as straight segment. Polyester ropes can be wet parked only if they have a qualified design that utilizes layers of cloth filters inside the rope jacket to resist soil ingression [2].

3.9.1.3 Hook-up of mooring lines to floating production unit

The pre-laid mooring lines may be sitting on the seabed for a period, from a couple of months to year, until the hull is constructed and finally towed to the site. To start the hook-up operation, the FPU hull is kept in position with help of few or more towing tugs. Two tugs connect to one side of the FPU and one or two tugs to the other side. Once the floating hull is towed to the site and weather condition is within the allowable limit, the hook-up procedure of the mooring lines can start. [2]

First, the pre-laid mooring lines picked up from seabed by the AHV, as shown in figure 3.15. Then the platform chain is connected to it on the deck of the AHV.

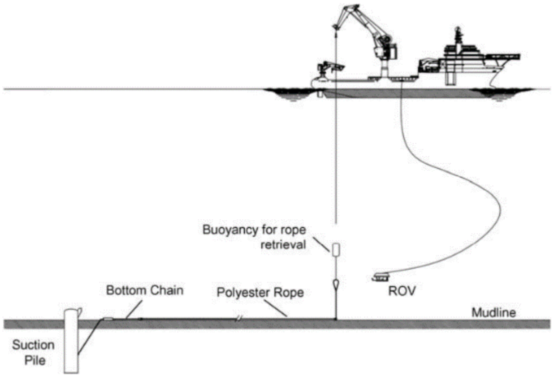


Figure 3.15. AHV is about to retrieve the pre-laid mooring line [2]

Work (pennant) wires are used as an aid to hand over the installation chain (temporary work chain) from the FPU to the AHV. The pennant wire is transferred to AHV by FPU’s crane. With that, the AHV can pull the installation chain onto its deck until it can be secured in the shark jaw, as showing in figure 3.16. while the FPU pays out the installation chain, the AHV moves slightly away from the FPU, pulling the end of platform chain on deck and secures it by other shark jaw. Platform chain and installation chain are both on the back deck as shown in figure 3.17 [2].

Figure 3.16. chain gets pulled though the towing pins (left) on the deck and secured by the shark jaw (middle) [2]

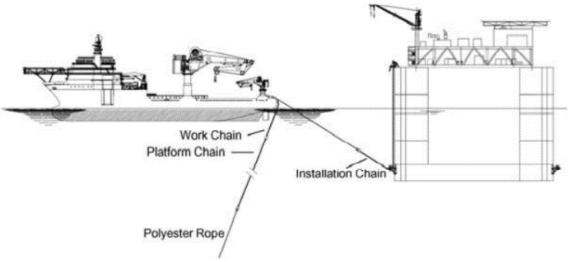


Figure 3.17: Platform and installation chains are brought to the AHV's deck for connection [2]

The two chains can now be connected by a special connecting link, i.e., LLLC link. Note that an LLLC links is designed to pass through fairleads and chain jacks like a common link. As the FPU pulls in the installation and platform chains using its winching equipment (e.g., chain jack), the AHV pays out a work wire to lower and release the mooring lines as shown in figure 3.18. The AHV is released from the installed line by ROV cutting the sacrificial wire sling. Final pull-in and tensioning will be completed by the FPU's chain jacks as shown in figure 3.19. The same procedure described above is repeated for the other three corners of the semisubmersible [2].

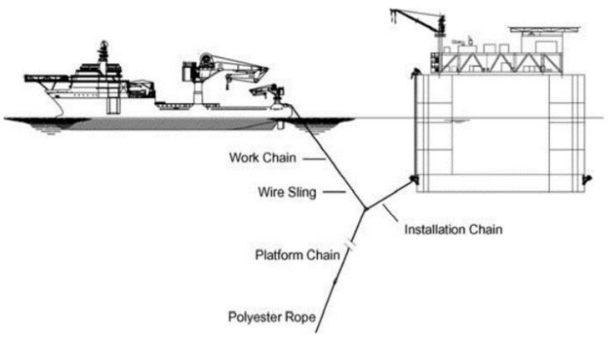


Figure 3.18. The hooked-up mooring line is lowered by the AHV [2]

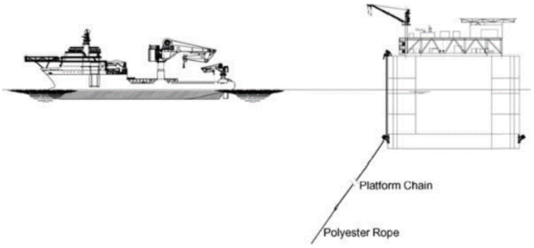


Figure 3.19. Hooked-up is complete, once the installation chain is pulled and stored in chain locker [2]

Once a specified number of mooring lines, such as four lines are hooked-up, the FPU reach a condition called “storm safe”. The partially installed mooring system has gained a limited capability of station-keeping to resist a storm of certain level. The procedure is then repeated for the rest of the mooring legs and the main procedure of the hook-up is complete [2].

If mooring line has any polyester rope segment an extra amount of tension is intentionally applied to remove the “construction stretch” in the polyester ropes [42]. Right after the hook-up polyester ropes are typically tensioned to about 40% of the minimum breaking load (MBL) for 2 hours to remove the construction stretch.

Because the chain jacks are normally not designed to have the extra tensioning capacity, a cross-tensioning technique can be used to stretch the polyester ropes. The technique utilizes two chain jacks at one corner to pull to tension up one mooring line at the opposite (cross) corner of the FPU. This two-to-one crossing tensioning technique allows a polyester rope to be pulled at high tension, such as 40% of its MBL. Once the construction stretches are removed according to the predefined procedure, the tensions are lowered to the desired pretension [2].

Following the completion of the mooring hook-up, a visual post-installation survey of the mooring system is performed by an ROV. The survey documents the as laid configuration of the mooring lines, notes any twist in lines and looks for any damage introducing during installation. It summarizes the pretension, line angles and positions of the installed mooring components.

3.9.2 Deployment and retrieval of temporary mooring

Installation procedures for temporary moorings are different from those permanent moorings. For temporary moorings, equipment such as anchors and wire ropes are carried by the subjected vessel which could be a MODU, floater, construction/work barge or tender assisted drilling. An AHV is used to deploy the mooring equipment. The subjected vessel will move after a few weeks or months to another site and the deployed mooring leg must be retrieved and brought back to the subjected vessel with help from AHV [2].

3.9.2.1 Rig mooring system for mobile offshore drilling unit

MODUs is generally moored with 8 to 12 anchors. Mooring lines are laid in a spread pattern. The deployment is conducted by AHVs that have large engine power to handle rig chain, wire, and anchors.

The typical method for deployment and retrieval of rig anchors on MODUs is to use a chaser from the AHV. A chaser is ring-shaped or hook-shaped tool that is used to chase (slide) along the mooring line toward the anchor and back again to a rig or handling vessel. Its function is to grab and move an anchor during a deployment or retrieval operation [2].

Figure 3.20 and 3.21 shows the procedure of deploy a rig mooring system. An AHV removes a rig anchor from the MODU’s bolster, and then runs the anchor line out the full distance to the anchor location with the anchor on the deck or on the roller. The AHV increase power until anchor line tension rises on the MODU winch tension meter. The anchor is over boarded and lowered over the stern roller. The anchor needs to always stay correctly oriented in the chaser. The AHV lays the anchor on the seabed, the MODU pulls in (heave in) the rig wire rope to drag and set the anchor. The embedment of rig anchors is obtained by dragging [2].

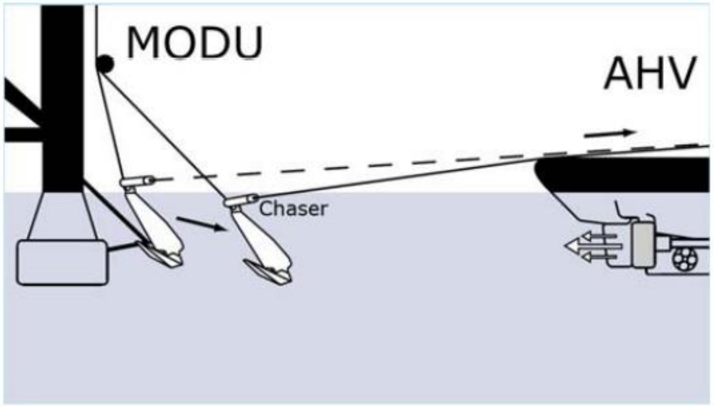


Figure 3.20. Rig anchor is unracked from MOUD’s bolster for deployment by AHV [6]

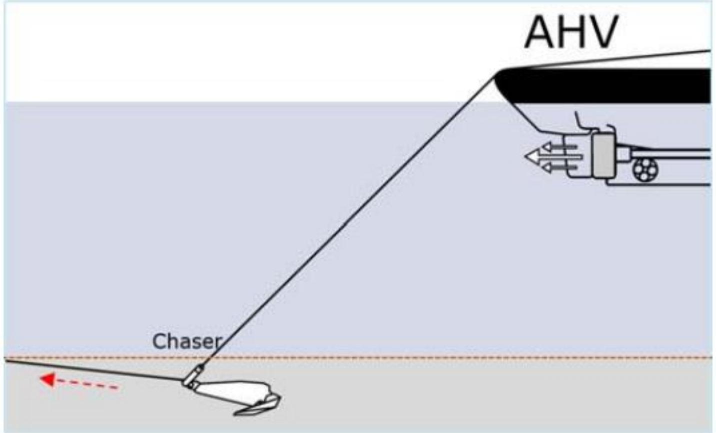


Figure 3.21. Rig anchor is getting embedded in seabed while handling by AHV [6]

3.9.2.2 Preset mooring system for mobile offshore drilling unit

Preset mooring has been commonly used with permanent mooring applications for FPUs. They can also be applied to the temporary mooring. A preset mooring is a system where most off-vessel components are installed prior to arrival of a MODU on location. The components in a preset system may include wire ropes, chain, polyester ropes and under water buoys [43].

With preset mooring, MODUs of older generations can considerably extend water depth limit Polyester rope, due to its light weight, can substantially help such an extension to deeper water. Generally, only one AHV is required for the preset mooring installation [43].

Advantage of using a preset mooring is that the MODU can come to the site and hook-up quickly, so that the drilling operation can be started sooner. With preset mooring increase the drilling uptime, which is often a priority. The disconnect and reconnected operation are simple, less likely to have complications, and have less potential for weather downtime [43].

3.9.3 Installation vessel

Mooring installation are normally performed by anchor handling vessel (AHV). They can also be done by other types of offshore vessels such as construction barges.

3.9.3.1 Anchor handling vessel

An AHV is an offshore supply vessel specially designed to provide anchor handling services and tow offshore platforms, barges, and production vessels. AHV is also known as anchor handling tug (AHT). AHVs have been used mainly for offshore drilling and production activities. They are serving multiple purpose including the following [2]:

- Handling anchors and mooring lines for drilling rig or production units

- Towing of floating structures in open water with subsequent positioning on site.
- Deploying subsea equipment
- Providing supply services

Anchor handling vessel requires high power, winch capacity, deck space, storage locker for rig chains and auxiliary handling equipment. Figure 3.22 shows a large AHV.

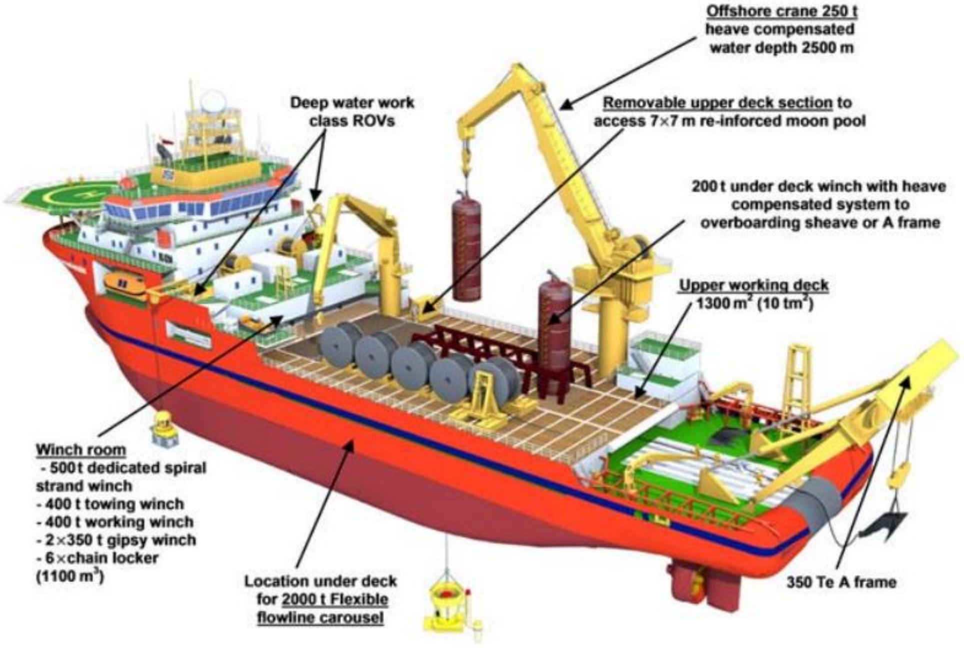


Figure 3.22. Anchor handling vessel [source SBM Offshore]

4 Fatigue analysis and corrosion protection

4.1 Introduction

Fatigue is a process of the cycle-by-cycle accumulation of damage in material undergoing fluctuating stresses and strains [36]. When the applied load varies with the time, the structure can subject to fatigue failure.

Fracture of a structural member as the result of repeated cycles of load or fluctuating loads is commonly referred to as a fatigue failure or fatigue fracture. A fatigue failure is caused by the cumulative effect of many load cycle. The region surrounding the origin of the fatigue fracture has a smooth, silky appearance. As the crack progress, the texture become rougher. Careful examination of this smooth part frequently reveals concentric rings or beach marks around the fracture nucleus. On a microscopic level, lines corresponding to each load cycle or group of cycles may be observed [36]

Fatigue failure is one of the critical failure modes of offshore permanent mooring systems. Fontaine et al [21] reviewed 107 offshore mooring accident and find out that the 29 mooring accident are primarily due to fatigue.

Traditionally, only mooring tensions are considered in mooring chain fatigue analysis. However , for fatigue analysis of mooring chain links connecting to chain wheels at fairlead, chain links passing over bending shoes, or chain linkers provided by chain hawse or chain stoppers, the effect of the out-of-plane bending (OPB) on the mooring fatigue should be considered [3, 22].

Figure 4.1 shows the cross-section of a mooring chain link due to fatigue from real incident. The cross-section is smooth and shows concentric rings, known as beach marks. The beach marks radiate from the origin and become coarser as the crack propagation rate increase. Each cycle of stress causes a single ripple and finally result in the whole chain link failure.

Figure 4.1. Broken surface showing beach marks [2]

In general, there are two distinct approaches in fatigue analysis as follow:

- T-N or S-N approach
- Fracture mechanics approach

The T-N or S-N approach use stress-life cumulative damage models to predict fatigue life consideration, the cumulative fatigue damage, where a failure occur after an number of loading cycles N, at a particular tension range T or stress range S. Fracture mechanics approach use fatigue crack growth models to examine the fracture behavior of mechanical elements under dynamic loading, where failure occurs if dominant crack have grown to critical length where the remaining strength of the component is insufficient. The fracture mechanics approach usually is more accurate for fatigue life prediction. However, the crack growth approach is not commonly used for fatigue design in offshore industry, mainly because of two difficulties. One is that the initial crack size is often unknown and second is that the model test data of crack versus stress are more expensive to obtain compared with S-N and T-N test data.

4.2 Miner's role

In the stress-life cumulative damage models, Miner's rule is applied to calculate annual cumulative fatigue damage. Also called Palmgren-Miner linear damage hypothesis, usually applied to calculate to annual cumulative fatigue damage [37, 38]. The annual cumulative fatigue damage ratio D is expressed as:

$$D = \sum \frac{n_i}{N_i} \tag{4.1}$$

where,

n_i = number of cycles per year within the tension range interval i.

N_i = number of cycles to failure at normalized tension range i.

as given by appropriate T-N or S-N curves.

1/D is the design fatigue life and should be higher than the field service life multiplied by factor of safety. For used mooring component, fatigue damage from previous operation should be considered. In Miner's rule approach the load sequence effect is not include the calculation, but load sequence effect is neglected in offshore mooring, thus this approach is recommended by industry standards and Class Rules.

4.3 Fatigue resistance of mooring components

Resistance to fatigue can be represented by fatigue curves, which are defined by few parameters. There are two approaches to defined fatigue curves:

- S-N curves, where the tension range T, is defined as tension divided by nominal cross-section area, and N is permissible number of cycles.
- T-N curves, where the tension T, normalized by suitable reference breaking strength (RBS), and N is the permissible number of cycles.

4.3.1 S-N curves for chain and wire ropes

If the mooring systems is designed according to DNV GL-OS-E301 [3], the following equation may be used for the component capacity against tension fatigue:

$$n_c(S) = a_D s^{-m} \tag{4.2}$$

This equation may be linearized by taking logarithms to give:

$$\log(n_c(s)) = \log(a_D) - m \ \log(s) \tag{4.3}$$

where,

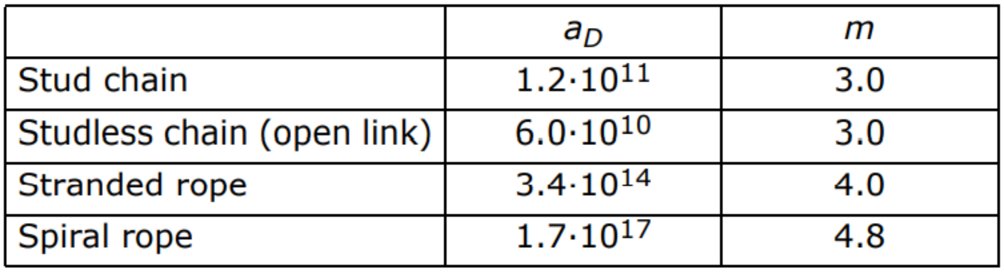
n_c = the number of stress range (number of cycles)

s = the stress range (double amplitude) in MPa

a_D= the intercept parameter of S-N curve

m = the slope of S-N curve

The parameters a_D and m represented in the Table 4.1 and S-N curve shown in the figure 4.2.



	a_D	m
Stud chain	$1.2 \cdot 10^{11}$	3.0
Studless chain (open link)	$6.0 \cdot 10^{10}$	3.0
Stranded rope	$3.4 \cdot 10^{14}$	4.0
Spiral rope	$1.7 \cdot 10^{17}$	4.8

Table 4.1. The S-N curve parameters [3]

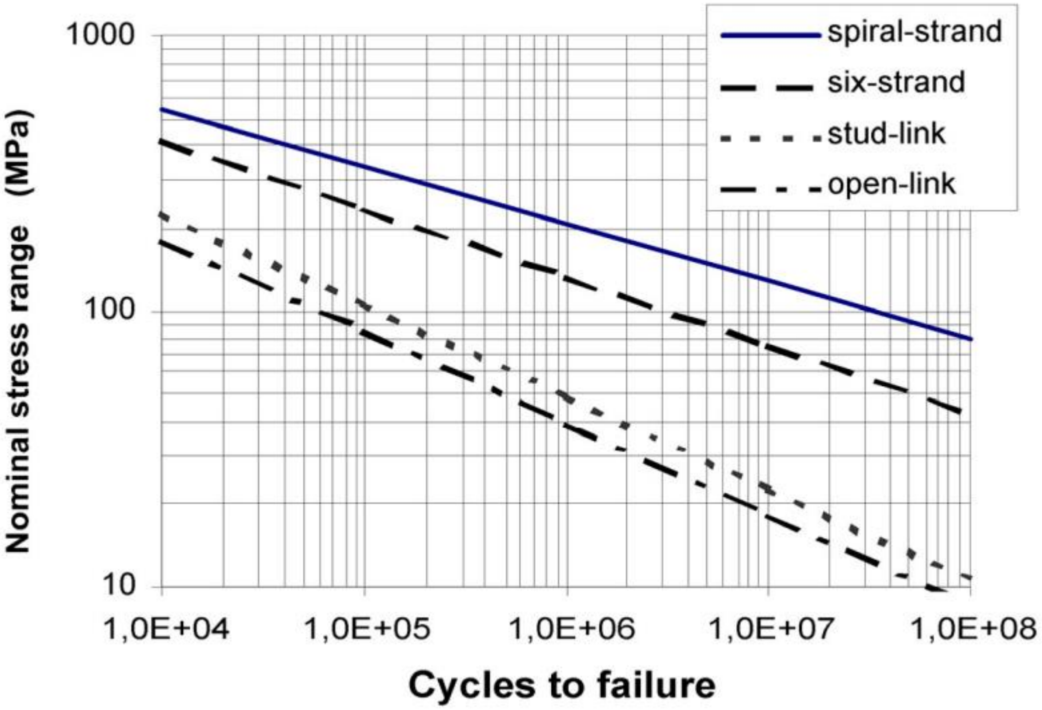


Figure 4.2. Design S-N curve [3]

Chain fatigue is more critical than the wire rope. Stud link chain has better fatigue resistance than the stud-less chain link. Stud reduce the stress concentration in the stud link and increase fatigue resistance. DNV GL -OS-E301 recommend safety factor of 3 for mooring line which inspected regularly.

The design equation for fatigue limit state (FLS) is defined by:

$$1 - d_c \cdot \gamma_F \geq 0 \tag{4.4}$$

where,

d_c = the characteristic fatigue damage accumulated because of cycling loading during the design lifetime.

$\gamma_F =$ the single safety factor for fatigue limit state

The fatigue safety factor for tension-tension fatigue γ_F shall cover a range of uncertainties in the fatigue analysis. The following value should be used for mooring lines which are not regularly inspected ashore:

$$\gamma_F = 5 \qquad when \qquad d_F \le 0.8$$

$$\gamma_F = 5 + 3\left(\frac{d_F - 0.8}{0.2}\right) \qquad when \qquad d_F \ge 0.8$$

where,

d_F = adjacent fatigue damage ratio, which is ratio between the characteristic fatigue damage d_c in two adjacent links taken as lesser damage divided by greater damage. d_F cannot be larger than one.

4.3.2 T-N curve for polyester ropes

DNV GL-OS-E301 [3] recommend similar procedure for tension-tension fatigue life for fiber rope as chain and steel wire. However, the fatigue capacity is related to the relative tension R rather than the stress. The fatigue should be calculated using R-N curve.

The following equation is used for the component capacity against tension fatigue:

$$\log(n_c(R)) = \log(a_D) - m \ \log(R) \tag{4.5}$$

where,

R = is the ratio of tension range to the characteristic strength

The parameters a_D and m give in Table 4.2.

	a_D	m
Polyester rope	0.259	13.46

Table 4.2. T-N fatigue curve parameters [3]

The fatigue safety factor γ_F is 60 for polyester ropes and shall cover a range of uncertainties in the fatigue analysis.

4.4 Fatigue analysis in frequency domain

The most efficient way to predict the fatigue in mooring systems is utilize the frequency domain analysis to derive tension variation for each presentative short-term sea state and then use close-form solution to calculate the cumulative fatigue damage. simple summation approach, combined spectrum approach and dual narrow band approach are three methods to derive overall fatigue damage.

4.4.1 Combined spectrum approach

The combined spectrum approach provides a simple, conservative approach. Which may be used in computing characteristic damage. The fatigue damage for one sea state can be calculated from the following equation:

$$d_{CSi} = \frac{V_{yi}T_i}{a_D}\left(2\sqrt{2}\sigma_{Yi}\right)^m \Gamma\left(\frac{m}{2}+1\right) \tag{4.6}$$

where,

T_i = is the duration of the environmental state:

n_i= is the number of stress in each state:

$$T_i = P_i \cdot T_D \qquad and \qquad n_i = v_i P_i T_D \tag{4.7}$$

The number of stress cycles in each state given by:

where,

v_i = is the mean-up-crossing rate in hertz of the stress process in state i

P_i = represent probability of occurrence of state i

T_D = represent the design lifetime of mooring component in second.

$\Gamma(.)$ = is gamma function

The standard deviation of the stress process is including both wave-frequency σ_{Wi} and low-frequency σ_{Li}.

$$\sigma_{Yi} = \sqrt{\sigma_{Wi}^2 + \sigma_{Li}^2} \tag{4.8}$$

The mean-up-crossing rate v_{yi} in hertz for one sea state is computed form the moments of combined spectrum:

$$v_{yi} = \sqrt{\lambda_{Li}v_{Li}^2 + \lambda_{Wi}v_{Wi}^2} \tag{4.9}$$

where,

λ = represent the normalized variance of the corresponding stress component

v = represent the up-crossing rate through the mean value, as computed from the second and zero order moments of the corresponding part of spectrum for subscripts Y, L and W.

$$\lambda_L = \frac{\sigma_L^2}{\sigma_L^2 + \sigma_W^2} \quad , \qquad \sigma_W = \frac{\sigma_W^2}{\sigma_L^2 + \sigma_W^2} \tag{4.10}$$

where,

σ_L = is standard deviation of low-frequency part of the stress process

σ_W = is the standard deviation of wave-frequency part of the stress process

4.4.2 Dual narrow band approach

The dual narrow-banded approach takes the result of the combined spectrum approach and multiplies by a correction factor ρ, based on the two frequency bands that are presented in the tension process.

$$d_{DNBi} = \rho_i \cdot d_{CSi} \tag{4.11}$$

The correction factor is given by:

$$\rho = \frac{v_P}{v_Y}\left[(\lambda_L)^{\frac{m}{2}+2}\left(1 - \sqrt{\frac{\lambda_W}{\lambda_L}}\right) + \sqrt{\pi\lambda_L\lambda_W}\,\frac{m\Gamma\left(\frac{1+m}{2}\right)}{\Gamma\left(\frac{2+m}{2}\right)}\right] + \frac{v_w}{v_y}\cdot(\lambda_W)^{\frac{m}{2}} \tag{4.12}$$

where subscript,

Y = refers to the combined stress process

P = refers to the envelope of the combined stress process

L = refers to the low-frequency part of the stress process

W = refers to the wave-frequency part of the stress process

For the envelope of the stress process, the mean up-crossing rate is given by:

$$v_P = \sqrt{\lambda_L^2 v_L^2 + \lambda_L \lambda_W v_W^2 \delta_W^2} \qquad (4.13)$$

where,

δ_W = is the bandwidth parameter of the wave-frequency part of the stress process, but is here set equal to 0.1

Value of gamma function give in Table.4.3.

m	*3.0*	*4.0*	*4.8*
$\Gamma\left[\frac{m}{2}+1\right]$	1.3293	2.0000	2.9812
$\Gamma\left[\frac{1+m}{2}\right]$	1.0000	1.3293	1.8274

Table 4.3. Gamma functions value [3]

4.5 Fatigue analysis procedure

For calculating fatigue damage due to low-frequency and wave frequency tensions, the procedure follows several steps:

- Determines environmental bins.
- Run mooring analysis for each bin.
- Determine the fatigue curve.
- Compute fatigue damage for each bin.
- Sum up the fatigue damages from all bins.

4.6 Out-of-plane bending fatigue for chain

First out-of-plane bending (OPB) fatigue discovered in the mooring legs of the Girassol buoy in 2002. OPB fatigue is identified as potential mooring failure mechanism [35-40].

Several mooring chains of an off-loading buoy failed after only 8 months of service. These chains were designed according to conventional fatigue assessment using API RP-2SK [22]. The mooring chain failure underwent significant mooring chain motions that caused interlink rotation. Traditionally neglected, there interlink rotation, where combined with significant chain tension can cause bending stresses in the chain links Out of Plane Bending (OPB) refers after to the bending of chain link out of its “main plane” as shown in figure 4.3 [29].

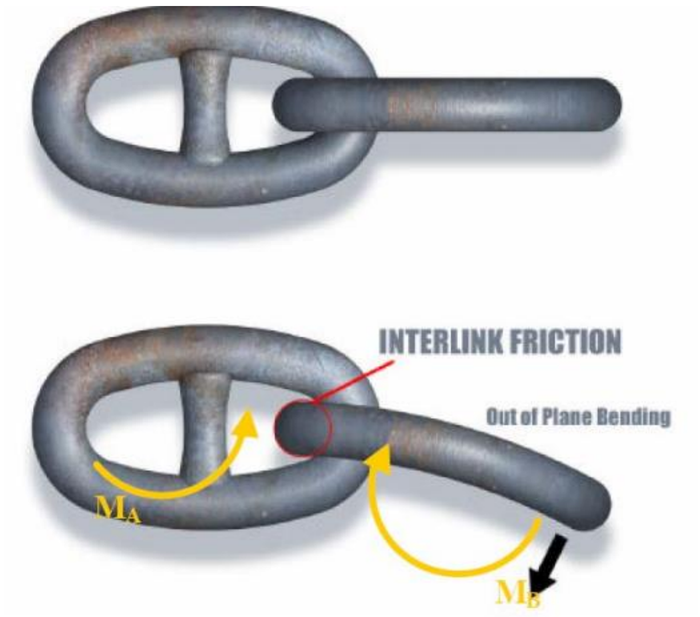


Figure 4.3. Out of Plane Bending [29]

4.6.1 Mechanism of out-of-plane bending fatigue

For chain with smooth interlink contact surfaces, it was general understanding that two adjacent links can rotate around each other due to interlink rolling and sliding. It was later found that links can lock to each other especially under high pretension in deep-water. Figure 4.4 shows the interlink locking that happen in the hawse pipe.

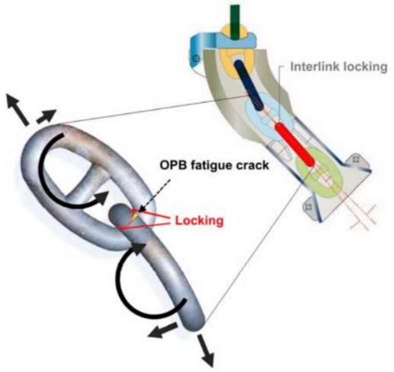


Figure 4.4. Chain OPB mechanism in hawse pipe [34, 35]

During the chain manufacturing process, chain links undergo proof loading test around 70% to 80% of their MBS. The proof loading leads to plastic deformation, especially in the grip area between the links. This change of geometry due to proof loading cause interlink rotational stiffness and leads to lock of chain links into each other.

Locking, stick-sliding, and sliding are three phases [35]:

- In locking phase, the chain links are locked in each other without any relative motion in the contact area. The chain link behaves as single rigid beam element. The bending moment increase linearly as the interlink angle increase. The slope of bending moment versus interlink angle in the locking phase is known as interlink stiffness.
- Stick-sliding phase can be considered as transition phase between locking and sliding. The relationship between bending moment and interlink angle become more nonlinear compare with locking phase.
- The relative motion of the adjacent links is characterized by sliding in the contact area. In this phase the bending moment remain constant with the increase of the interlink angle.

During locking and stick-sliding phases the magnitude of the bending stress is significantly higher than the bending stress that develops during rolling phase in nonproof loaded chain links. In theory, OPB fatigue can occur at any location where adjacent chain links undergo relative angular movement.

Crack initiation point of the OPB fatigue and tension-tension (TT) fatigue occur in different location in the chain link as shown in figure 4.5.

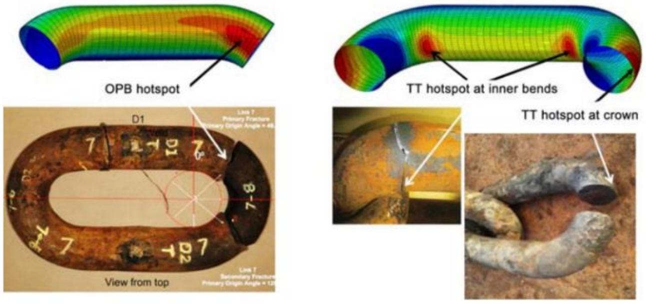


Figure 4.5. Comparison of the hot spot locations between OPB loading and TT loading [34]

In the case of OPB loading the hotspot located in the bend region, close to the contact area between the two links, but for TT loading the locations are in the crown and inner bends.

4.6.2 Out-of-plane bending fatigue assessment

Compared with the traditional TT fatigue of mooring chain which has been studied for many years, OPB fatigue is relatively novel. The out-of-plane bending mooring chain involves a complex mechanism so that is difficult to determine whether the OPB fatigue assessed for a particular design of fairlead or hawse pipe.

Some guidance has been published that recommend and summarize OPB fatigue assessment methodology [35-40]. The OPB fatigue analysis performed in the following main steps:

- Develop fatigue sea state: The process for developing OPB fatigue sea states is like the TT fatigue analysis.
- Develop interlink stiffness and stress concentration factor (SCF): The chain interlink bending stiffness describes the relationships between the interlink angle and the nominal bending moment generated between two adjacent chain links. The finite element analysis (FEA) can be used to estimate bending stiffness and SCF at OPB hotspots. In early design phase without conducting FEA analysis of chain testing, the interlink stiffness model and SCF recommend by Bureau Veritas (BV) [39] can be considered. At OPB hotspot location the SCF recommend as function of chain pretension level with minimum value of 1.15.
- Perform global response analysis and local modeling: The objective of this step is to estimate the time-series of tension and bending moment component of the chain links in specific fatigue sea state.
- Calculate total stress and count cycles: After global response analysis, stress calculation and cycle counting, the time-series of tension and primary and secondary moment components are used to calculate the nominal tensile, OPB and in-plane bending (IPB) stress components in the affected links using the moments of area of the chain links. The total fatigue damage is calculated based on S-N curve with Miner's rule.

4.6.3 Stress concentration factor (SCF)

Mooring analyses and static OPB and IPB simulations provide time series of tension loads and interlink moments at contact area. To obtain stresses due to TT, OPB, and IPB loadings stress concentration factors on TT load and OPB interlink moments are be evaluated through FEM calculation. Figure 4.6 shows the critical hotspot on chain link for combined fatigue damage of top chain [39].

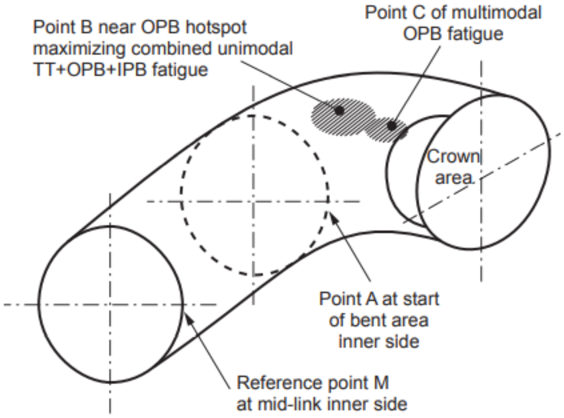


Figure 4.6. Critical hotspot on chain link for combined fatigue of top chain [39]

4.6.4 Determination of critical hotspot

As the TT, OPB and IPB hotspot stress are in different part of the chain link, the fatigue failure location may vary depending on the magnitude of each loading. Thus, different stresses at different hotspots have be assessed in fatigue. Additionally, in OPB hotspot are, when approaching interlink contact area, stresses are uniaxial anymore and multiaxiality of stress is to be addressed by appropriate multiaxial fatigue method such as Dang Van Criteria [39]. Figure 4.6 shows the location of hotspot stresses as follows [39]:

- Pure TT hotspot is at hotspot A.
- Uniaxial OPB hotspot maximizing TT, OPB and IPB effects at location B.
- Multiaxial OPB hotspot with multiaxiality effects closer to the contact area at location C.

Cyclic stresses and corresponding stress concentration factors for different loading are defined as follow with d the un-corroded nominal diameter of chain [39]:

$$SCF_{TT} = \frac{\Delta\sigma_{TT}}{\Delta\sigma_{TT,nom}} \tag{4.14}$$

and,

$$SCF_{OPB} = \frac{\Delta\sigma_{OPB}}{\Delta\sigma_{OPB,nom}} \tag{4.15}$$

with,

$$\Delta\sigma_{TT,nom} = \frac{2\Delta T}{\pi d^2} \tag{4.16}$$

$$\Delta\sigma_{OPB,nom} = \frac{16\Delta M_{OPB}}{\pi d^3} \tag{4.17}$$

For stud-less chain, IPB stresses and corresponding stress concentration factors is defined ass following [39]:

$$SCF_{IPB} = \frac{\Delta\sigma_{IPB}}{\Delta\sigma_{IPB,nom}} \tag{4.18}$$

with,

$$\Delta\sigma_{IPB,nom} = \frac{2.33\Delta M_{IPB}}{\pi d^3} \tag{4.19}$$

For stud-link chain, IPB stresses and corresponding stress concentration factors is defined as following [39]:

$$SCF_{IPB} = \frac{\Delta\sigma_{IPB}}{\Delta\sigma_{IPB,nom}} \tag{4.20}$$

with,

$$\Delta\sigma_{IPB,nom} = \frac{2.06\Delta M_{IPB}}{\pi d^3} \tag{4.21}$$

These stress concentration factors can be estimated through adequate FEM calculation calibrated by full scale model test on chain [39].

Stress for fatigue damage computation are to be calculated considering the material loss due to corrosion at mild life of the unit. The effect of a uniformly spread loss of material of the TT, OPB and IPB nominal stresses as follows [39]:

$$d_{correded} = d_{correded} - \frac{L_d}{2} r_{corr} \tag{4.22}$$

$$\Delta\sigma_{TT,nom} = \frac{2\Delta T}{\pi d_{correded}^2} \tag{4.23}$$

$$\Delta\sigma_{OPB,nom} = \frac{16\Delta M_{OPB}}{\pi d_{correded}^3} \tag{4.24}$$

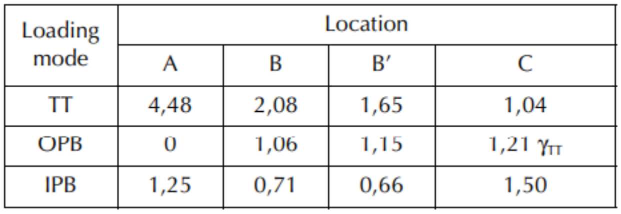
$$\Delta\sigma_{IPB,nom,studless} = \frac{2.33\Delta M_{IPB}}{\pi d_{corroded}^3} \tag{4.25}$$

with,

L_d = Design life of the unit

r_{corr} = Loss of diameter due to corrosion per year.

Stress concentration factors for stud-less chain for location A (pure TT), B and B' (uniaxial OPB) and C (multiaxial OPB) are defined in table 4.4 [39].



Loading mode	Location			
	A	B	B′	C
TT	4,48	2,08	1,65	1,04
OPB	0	1,06	1,15	1,21 γ_{TT}
IPB	1,25	0,71	0,66	1,50

Table 4.4. Stress concentration Factors [39]

Due to multiaxiality of stress of location C, the mean stress effect cannot be neglected for OPB loading and a mean stress correction factor γ_{TT} is be introduced multiaxial OPB SCF as follows [39]:

$$\gamma_{TT} = 1 + 0.9\left(\frac{P}{MBL} - 0.15\right) \qquad (4.25)$$

not being less than 0.95

where,

P = is mooring line pretension, in Kn

MBL = is mooring line breaking strength , in Kn

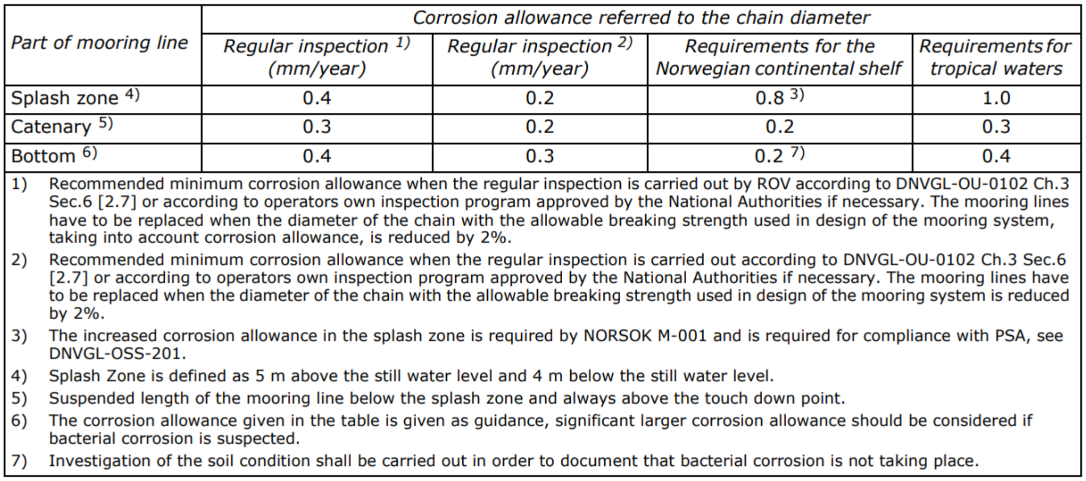
For the stud-link chain, it is recommended to perform a defined FEM analysis under TT, OPB and IPB loading modes [39].

4.7 Corrosion

Chain corrosion is inevitable, given the nature of the material and the harsh environment in which it is deployed. Since chain is typically not coated or protected, it is subjected to general corrosion as would be expected for any bare steel structure. This lack of protection is typically accounted for in design by imposing a wear and corrosion allowance on the chain with some variation of the allowance depending on the design code and the location of the chain with respect to the water surface and the seabed. In addition to corrosion, wear between links can also be an issue when the relative motions between links exceed 0.5 degrees (depending on tension level) or when the chain is in dynamic contact with a hard surface either at the fairlead or the seabed [20].

Typical requirements for wear and corrosion vary between industry guidelines and design codes and can range from 0.2 mm/year to 0.8 mm/ year depending on weather the chain is an almost static position on the seabed versus in the active splash zone area. Table 4.5 shows corrosion allowance [3] This corrosion and wear allowance is generally applied to the new chain component size and assume a uniform reduction in bar diameter and thus minimum break strength. While this may approximate the brake strength of the corroded chain, the impact on fatigue life is typically not addressed other than the impact of scaling of fatigue loads with corroded break strength, i.e. the stress concentration factors are unchanged.

Depending on the type of corrosion, e.g., pitting corrosion versus general corrosion and location of the corrosion on a link, one could expect the stress concentration factors to be different from those derived from a pure tensile loading and the corrosion could possibly initiate cracks that would accelerate fatigue at that location [20].



Part of mooring line	*Corrosion allowance referred to the chain diameter*			
	Regular inspection 1) *(mm/year)*	*Regular inspection* 2) *(mm/year)*	*Requirements for the Norwegian continental shelf*	*Requirements for tropical waters*
Splash zone 4)	0.4	0.2	0.8 3)	1.0
Catenary 5)	0.3	0.2	0.2	0.3
Bottom 6)	0.4	0.3	0.2 7)	0.4

1) Recommended minimum corrosion allowance when the regular inspection is carried out by ROV according to DNVGL-OU-0102 Ch.3 Sec.6 [2.7] or according to operators own inspection program approved by the National Authorities if necessary. The mooring lines have to be replaced when the diameter of the chain with the allowable breaking strength used in design of the mooring system, taking into account corrosion allowance, is reduced by 2%.

2) Recommended minimum corrosion allowance when the regular inspection is carried out according to DNVGL-OU-0102 Ch.3 Sec.6 [2.7] or according to operators own inspection program approved by the National Authorities if necessary. The mooring lines have to be replaced when the diameter of the chain with the allowable breaking strength used in design of the mooring system is reduced by 2%.

3) The increased corrosion allowance in the splash zone is required by NORSOK M-001 and is required for compliance with PSA, see DNVGL-OSS-201.

4) Splash Zone is defined as 5 m above the still water level and 4 m below the still water level.

5) Suspended length of the mooring line below the splash zone and always above the touch down point.

6) The corrosion allowance given in the table is given as guidance, significant larger corrosion allowance should be considered if bacterial corrosion is suspected.

7) Investigation of the soil condition shall be carried out in order to document that bacterial corrosion is not taking place.

Table 4.5. Corrosion allowance for chain [3

5 Integrity management and life extension

5.1 Introduction

Inspection prevent mooring incidents caused by poor condition of mooring components. Along the mooring line there are few areas that are prone to integrity issues [26, 27]. These are need special attention during inspection. The top end at vessel interface and touch down area at the seabed are most problematic areas. They are subjected to high degradation and need closely inspected. Splash zone are more potentially for corrosion of chain. All connectors and wire rope termination are critical components because discontinuity in weight per length can increase bending and wear.

5.2 Inspection

There is limited degradation for mooring component during the design phase, such as corrosion and wear. Inspection is important to confirm that the degradation is within the design limit. offshore structure follows a framework for in-service inspection defined in Class Rules. The framework is based on the long-term practices, established by the shipping industry. Periodic surveys can classify as annual, intermediate, and special surveys [2].

American Petroleum Institute Recommended Practice (API RP) 2I [22] and Offshore standard, DNVGL-OS-E301[3] provides limited guidance on potential damage mode for each type of mooring components.

Inspection of permanent mooring systems has two stages, as built and in-service. As-built survey should be performed once mooring systems hooked-up to the floater and tensioned to design value and confirm that there is no damage during installation and anchor leg is connected as design. Visual inspection and videotaping performed with remotely operated vehicle (ROV) from the anchor to the fairlead [2].

Class Rules classified the inspection plan as follows:

- Annual survey-Mooring component above the waterline should inspected in annual basis. Attention should be paid to chain with contact to winches, chain stopper/fairlead and splash zone.
- Intermediate survey-Depending in which Class Society is used. It is an underwater survey.
- Special survey-Occur every 5 years. Where possible the mooring component raised to the surface for detail inspection. Special survey includes the annual inspection requirement, any mooring component near the touch down point, any damage report from earlier and the condition of the corrosion protection.

5.3 Inspection method

Inspection method for Mobile Offshore Drilling Unit and permanent mooring is different. For MODU inspection the drilling vessel can take into dockside and the chain laid out in dry surface for inspection. Normally this type of inspection can be done with other major structural work or with special survey. Figure 5.1 shows the inspection method [2].

Figure 5.1: Dockside inspection method for MODU chain [6]

In another method the drilling vessel stay offshore, and the chain inspected with help of workboat. The chain in chain locker is paid out fully and inspected by an inspector standing close to the windlass while the chain slowly taken back to the chain locker. The benefit of this method is, there is no need for dock facilities [2].

Inspection of the permanent mooring are in-place. Component above the water line are inspected visually or by nondestructive technique such as magnetic particle inspection (MPI). The underwater component inspected by ROV and in shallow water with help of divers [2].

5.3.1 General inspection

General visual inspection is the common method for overall inspection. The inspection done by slow ROV flight or divers swim past the item being inspected. The most common tool for inspecting the mooring line is ROV. The inspection can be done from a dynamic positioning (DP) vessel, that equipped for the operation. Videotaping capability is a requirement that allow a complete real-time inspection of the process. Figure 5.2 shows a video image taken by ROV during inspection of wire rope [2].

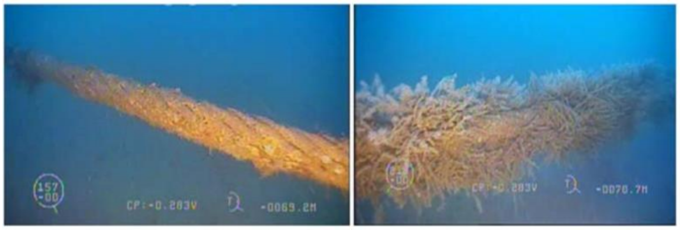


Figure 5.2. Underwater inspection of wire rope [2]

5.3.2 Close-up visual inspection

Close-up visual inspection is for mooring component. Its purpose is to assess the condition of the subject component and measure any anomaly. Cleaning of the area will normally be required. Figure 5.3 shows a mooring chain before and after cleaning. Figure 5.4 shows rope-access specialist take diameter measurement of mooring chain with caliper.

Figure 5.3: Marine-fouled chains before and after cleaning by the diver [23]

Figure 5.4. Diameter measurement of chain with caliper [25]

5.3.3 Nondestructive examination technique

Nondestructive examination (NDE) techniques used to identify surface crack. They are used in critical location identified by analysis or in-service experience. The NDE techniques most commonly are used [2]:

- Magnetic particle inspection (MPI)
- Dye penetrant (DP) where no coating is present
- Eddy current inspection for detection of surface breaking indications through paint coating

MPI and DP are the most appropriate method for detection of fatigue crack when the components are dry in air [2].

5.3.4 Inspection of chain

The harsh environment which mooring chain exposed can lead to various problems:

- Corrosion-General corrosion for chain can be seen in the splash zone. Figure 5.5 shows this type of corrosion.

Figure 5.5. corrosion chain above water line [24]

- Pits-Large pits can develop in submerged chain, caused by sulfate reducing bacteria and this is key contributor to MIC (microbiologically influenced corrosion) [28].
- Wear or abrasion-Wear between links and wildcat of fairlead or between two adjacent links reduce the chain diameter. The diameter reduction reduces the load carrying of the chain and may failure in future. Chain wear also happen in touch down area as shown in figure 5.6. [25].

Figure 5.6. Ground chain and touch down chain with lose of material in one side [25]

- Cracks-Surface crack, flash-welded cracks and stud-weld cracks may propagate under cycling loading and resulting chain failure.
- Loose or missing studs-A stud chain without stud resulting higher bending stresses and reducing fatigue life of the chain, which cause by excessive corrosion between link and stud or by abusive handling of chain.
- Gouges-Physical damage to the chain surface such a cut or pit which arise stress and may promote fatigue failure.
- Elongations-Excessive permanent elongation may cause a MODU chain to function improperly in the wildcat and resulting in bending and wear of the link. Wear in the grip area of the chain and working loads excess of proof load will result in permanent elongation of chain.

5.3.5 Inspection of wire rope

- Broken wires-Broken wires at termination, indicate high stresses at the termination may cause by incorrect fitting of termination, fatigue, overloading or mishandling during deployment or retrieval and upset the balance of the load carried by the strand. Figure 5.7 shows such problems [2].

Figure 5.7. Broken wires at wire rope termination [32]

- Corrosion-Server corrosion may reduce the elasticity of rope. Reduction of outer wire is common problems and shall detected visually. Irregular surface will result stress cracking and accelerate fatigue failure.

- Change in rope diameter-The rope diameter can be reduce by external wear, interwire and inter-strand wear, stretching of the rope and corrosion. Excessive reduction of diameter reduces strength of the wire rope.
- Wear-External wear of wire rope can cause by dragging of the wire ropes with hard seafloor during deployment of anchor or retrieval. Internal wear cause by friction between individual strand and wire ropes. Reducing strength of wire ropes due to reducing of cross-sectional area of wire rope.

5.3.6 Inspection of fiber rope

- Cut or abrasion-Fiber robe damage is often because of contact with sharp edges during deployment or retrieval, dropped object or contact with other installation activity.
- Soil ingress or marine growth-Ingress of soil particles may occur when rope meets seafloor during installation. Marine growth can be harmful for fiber rope if penetrate through the jacket into the load carrying fibers.

5.3.7 Inspection of connecters and anchor

For MODU mooring components, the inspector visually inspects all mooring components such as anchor shackles, swivels, open links and connecting links. In addition, certain critical areas in mooring line inspected by MPI. One critical part in connecting shackle is the pin with nut. It is important to ensure that the pin maintain its integrity [2, 20].

5.4 Monitoring

It is becoming increasingly common for operators to want to supplement ROV and or diver inspection of the entire anchor leg system with a direct means of determining the integrity of the anchor leg system and its station keeping performance. Typically, the requirement is for measuring anchor leg tension and vessel position with a means of providing alarms in case of exceedance of pre-determined bounds. However, the majority of the permanent mooring systems for floating production facilities are designed to operate for all design and survival conditions passively, i.e., no adjustment to anchor leg system is required to maintain position or minimize anchor leg tensions, unlike for many MODUs. From this perspective, most permanent mooring systems have anchor leg terminated in chain stoppers rather than winches that monitor tension, liken on MODUs. From the an engineering perspective, direct tension measurement of each anchor leg tension is the best solution to theoretically monitor a mooring system, as it can be used for simple functions like line break detection and anchor leg configuration in calm water to detailed time history of loads and responses [2, 20].

Monitoring is an important part of the asset integrity management. The main objective of monitoring is continuously verifying the condition or performance of the mooring line and provide input for the assessment of mooring integrity [2, 20].

Industry standard and Class Rule provide guideline on the mooring monitoring systems, depend on the type of operations. In general, a MODUs is always equipped with line tension and offset monitoring system to meet the stringing requirements for drilling operation. Floating production vessels are typically equipped with position monitoring systems. Tensioning mooring systems are required in case if the mooring line connect with a winching/tensioning device.

The most important parameter to observe is a failure or loss of tension in mooring line. A failure can be detected through the loss of tension, a sudden change in line angle, a drop to the seabed or a sudden shift in facility equilibrium position [2, 20].

Underwater inspection should still play a big role in monitoring anchor leg systems, baseline measurement is important to serve as a benchmark. Quantitative measurement should be taken consistently, there are too many qualitative ROV inspections performed at a great cost with limited useful data from a monitoring perspective [2, 20]

Chain should be baselined by identifying, marking, and measuring representative chain links in different corrosion and wear zones for reference during future inspections. It is especially important to record these measurements for the chain links in the fairlead and in the splash zone. Monitoring anodes in spelter sockets etc. provide important feedback on corrosion and provide an early warning if depleted prematurely [2, 20].

5.5 Monitoring method

5.5.1 Monitoring visually

Visual monitoring by the crew or surveyors with or without a closed-circuit TV system is a common practice for FPSO and FSO with an external turret mooring systems above water line as shown in figure 5.8.

Figure 5.8. Monitor screen in control room for an FPSO [2]

5.5.2 Monitoring tension

Some advanced monitoring methods provide line tension in real-time [2]:

- Direct tension measurement using load cells-This is a typical setup for vessel use chain jacks. Load cell are built into the chain stopper or foundation of winching equipment such as a chain jack sitting on the deck.
- Indirect tension measurement using inclinometers-This is a typical arrangement for an FPSO with internal turret mooring system. The inclinometers are fitted on the hawse pipes around the chain table at bottom of the turret which submerged under water. The measured angles on the top of mooring line can be converted to calculated tension either from catenary calculation or hook-up table. Note that this method can introduce uncertainty since the dynamic effects are not include in calculation. Figure 5.9 shows inclinometer on top of chain.

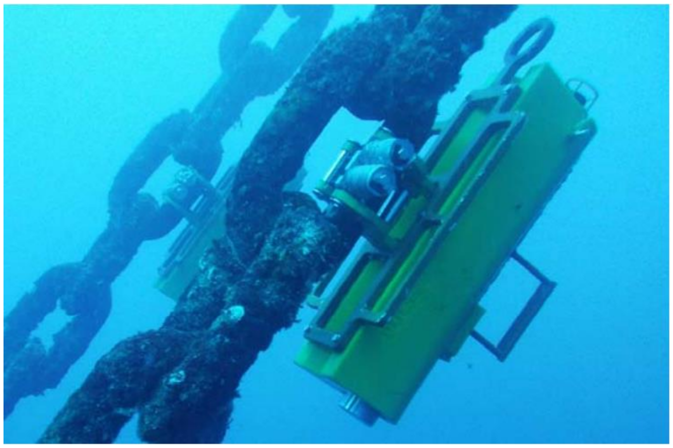


Figure 5.9. Inclinometer installed on top of chain [2]

5.5.3 Monitoring vessel position

A reliable and cost-effective alternative to monitor the performance of the mooring systems is to observe the platform position over time. Position monitoring can be achieved by installing a position mooring system onboard the vessel based on differential navigation systems. DGPS (Differential Global Positioning Systems) [2].

5.6 Failure of mooring systems

For permanent mooring systems failure can occur at any components in mooring line systems. Most of the failure occurred at interface or discontinuity. Such interface can be fairlead between the line and vessel, at connecter between types of line or connection of spring buoys, clump weight s, tri-plate, etc., figure 5.10 shows location of failure along the mooring line [27].

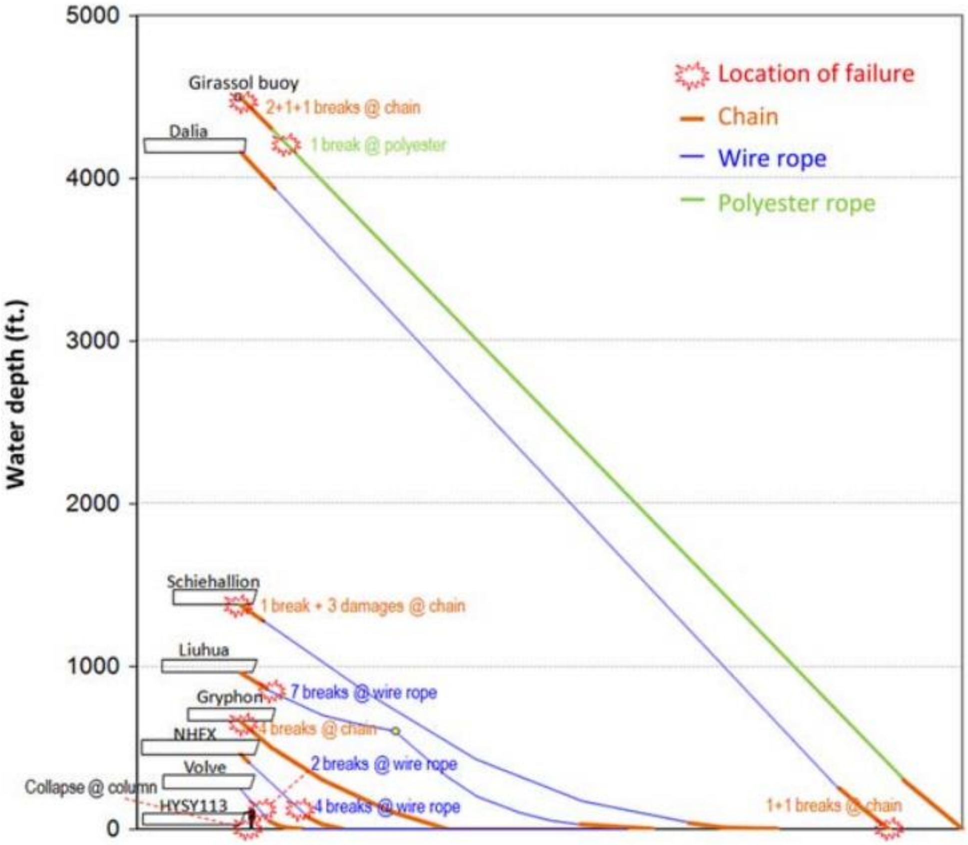


Figure 5.10. location of failure along the mooring line [27]

During design, the mooring line modeled as simple tension only element with section properties reflection the component along the line. Compression, bending and torsion have been ignored but studied/experience shown that they are also cause the mooring line failure.

5.6.1 Failure location of mooring line

For mobile moorings systems, wire rope seems to be the most problematic component compare to the chain and connectors. Over 80% of failure occurred in fairlead or near fairlead [31].

Six-strand or eight-strand wire rope are widely used for MODU mooring line to keep the vessel in station-keeping. Wire rope are lighter, easy to handle and deployment. Wire ropes are made of small bundle wire and easier to be damage and require more attention to assure integrity for safe operations. Figure 5.11 shown the critical location of the wire rope [32].

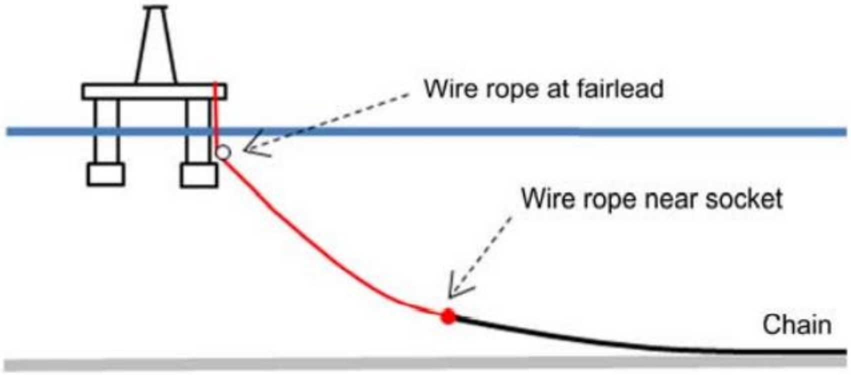


Figure 5.11. Critical location of wire rope [32]

The first weak point is the part passing through the sheave in fairlead. In this part the wire rope meets the highest tension due to its own weight. In addition, bending and compression stresses occur in the sheave as well [33]. Figure 5.12 shows such a problem.

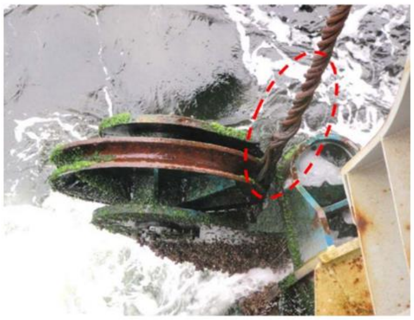


Figure 5.12. Damage wire rope in fairlead [32]

The second weak point location is at socket termination. Broken wire rope often can be found in this location. Wire near the socket termination experience cycling bending and torsional loads such that the wires at the outer layer may leads to fatigue due to localized stress concentrations. If the socket termination is located near the touch down area, it can suffer from repeated beating to the seabed and get broken quickly and should inspected after each deployment [2].

5.6.2 Percentage distribution of mooring failure by component type

Chains, connecters including shackle, H-link, tri-plate, and wire ropes are the most problematic components for permanent mooring systems as shown in figure 5.13 from year 2001 to 2012, [27].

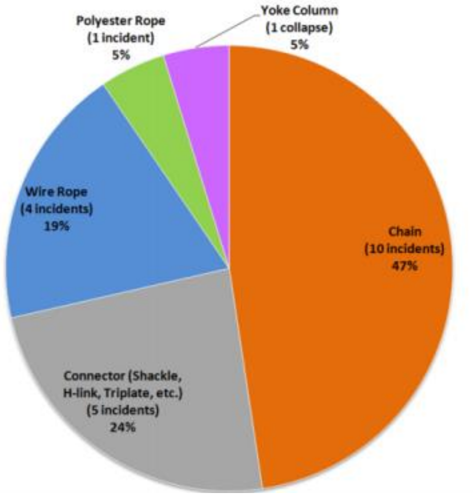


Figure 5.13. Percentage of failures by components types for permanents mooring [27]

Chains failures contribute 47% of the incidents. Chains manufacturing is a complex process, therefore represent many incidents while chains have been used more in mooring systems. After the chains, connectors and wire represent high rate of failures. Design of connectors have been proving based on lessons learned. Most of the wire ropes failure were unsheathed but nowadays most of the wire ropes for permanent mooring is sheathed and protect the wire against corrosion. Polyester rope represents only 5% of the failures. Time have proved that the polyester ropes are very reliable, and therefore become the most favored component for deep-water mooring due to its light weight and good reliability [27].

5.6.3 Percentage distribution of chain failure by cause

Figure 5.14 shows that chain failures were dominated by corrosion and fatigue. While the wire rope dominated by damage during installation. The significant difference in event base (installation damage, mechanical damage, extreme loading) and time based (corrosion , fatigue) failure modes between chain and wire rope suggest that there may be an opportunity to optimize the types of control measures employed at the appropriate lifecycle phase such that these threats can be eliminated or reduced [21].

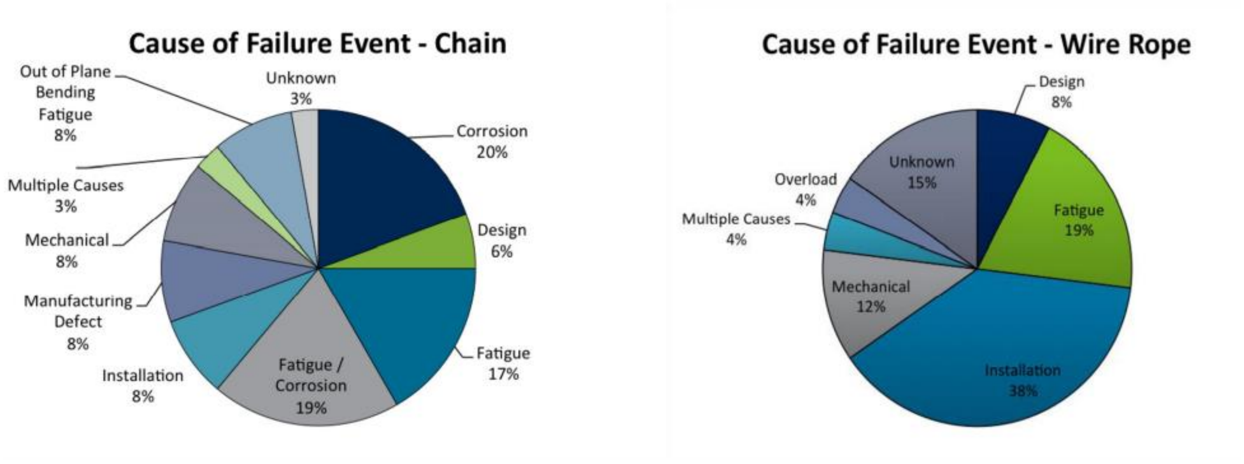


Figure 5.14. Cause of failure events of chain link (left) and wire (right) [21]

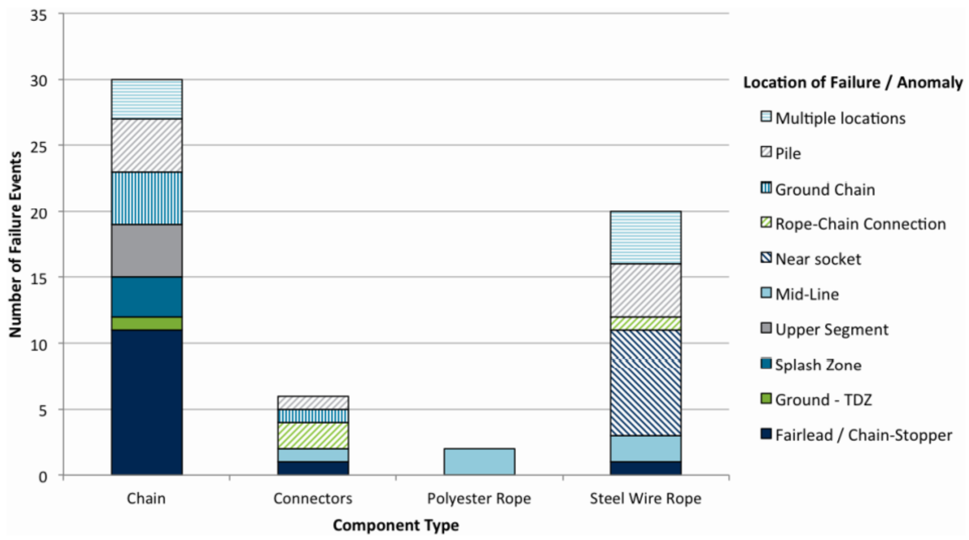


Figure 5.15. Failure event location by component type [21]

Most of the chain failure occurred in the upper sections and chain stopper/fairlead as shown in figure 5.15. This indicated that the behavior of chain links in this region should carefully evaluated during design, to reduce the risk of failure. Wire rope failures were most in termination. This indicated that local behavior at mass/stiffness discontinuities at wire termination carefully evaluated during design, to minimize the risk of failure. Polyester failure occurred mid-line, caused by contact of mooring line by a dropped or dragging object [21].

5.7 Failure mechanisms

Study shows that there were other failure mechanisms rather failures due to weather overload. Such failure mechanisms are [27]:

- Out-of-plane bending fatigue (OPB)
- Pitting corrosion
- Flawed flash weld
- Chain (knotting) due to twist
- Unauthorized chain repair.

5.7.1 Fatigue chain due to out-of-plane bending (OPB)

Out-of-plane bending (OPB) fatigue of mooring chains was first identified as failure mechanism after the failure several mooring chains of Girassol's deep-water offloading buoy in 2002. The discovery of this failure mechanism result in a Joint Industry Project (JIP) that ran from 2007 to 2013 and provide valuable insights as well as design methodology [34]. Figure 5.16 shows the chain top arrangement and OPB fatigue.

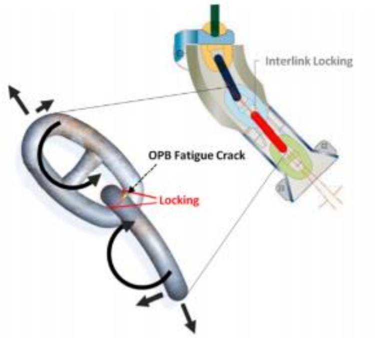


Figure 5.16. Chain OPB mechanism inside the hawse pipe of Grassol buoy [35]

5.7.2 Chain with severe corrosion

Corrosion has been the main reason for several preemptive replacement of mooring systems. Severe corrosion found on steel mooring components (CSMC) at several sites worldwide. Both general and pitting corrosion can be damaging the top chain in certain region in the world.

5.7.3 Deficient chain from manufacturing

Several mooring lines failed due to deficiencies that were introduced to the surface chain when improper weld-repair were done by the manufacture, to patch manufacturing defect. Chain with manufacturing defects must be scrapped.

6 Design of a Mooring Chain in ABAQUS (Case Study)

6.1 Mooring chain dimension

A mooring chain is composed of a series of interconnected links. Which transmit the applied load from one link to the next by direct contact. Mooring chains are manufactured out of hot rolled low alloy carbon steel. Offshore Standard DNV GL-OS-E302 [4] and IACS W 22 [13] define different grades of mooring chain. The difference between each grade relates to the required mechanical properties. K_t point and Crown regions have the highest ratio between the local stress and nominal stress and illustrated in figure 6.1 These regions can be determined from an elastic analysis of the chain under tension. Mooring chain during manufacturing undergo proof loaded, which is 70% of the minimum of breaking load (MBL). The Minimum Breaking Load (MBL) is the minimum that the chain segment of at least three chain links must withstand during 30 s without fracture. It is defined as a function of the material grade and diameter of the chain. The imposed fatigue loading will be referred as a percentage of the Minimum Breaking Load (MBL). Table 6.1 presents the value of the Proof Load and Minimum Breaking Load (MBL) for the diameter 127mm [10, 11].

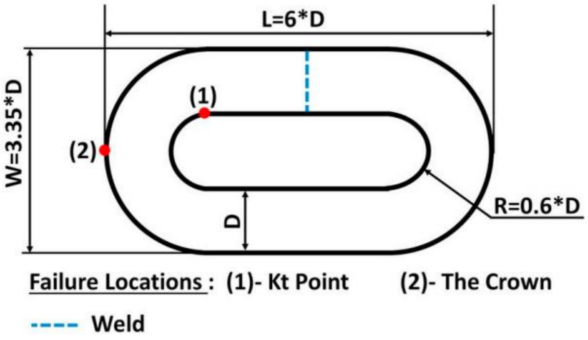


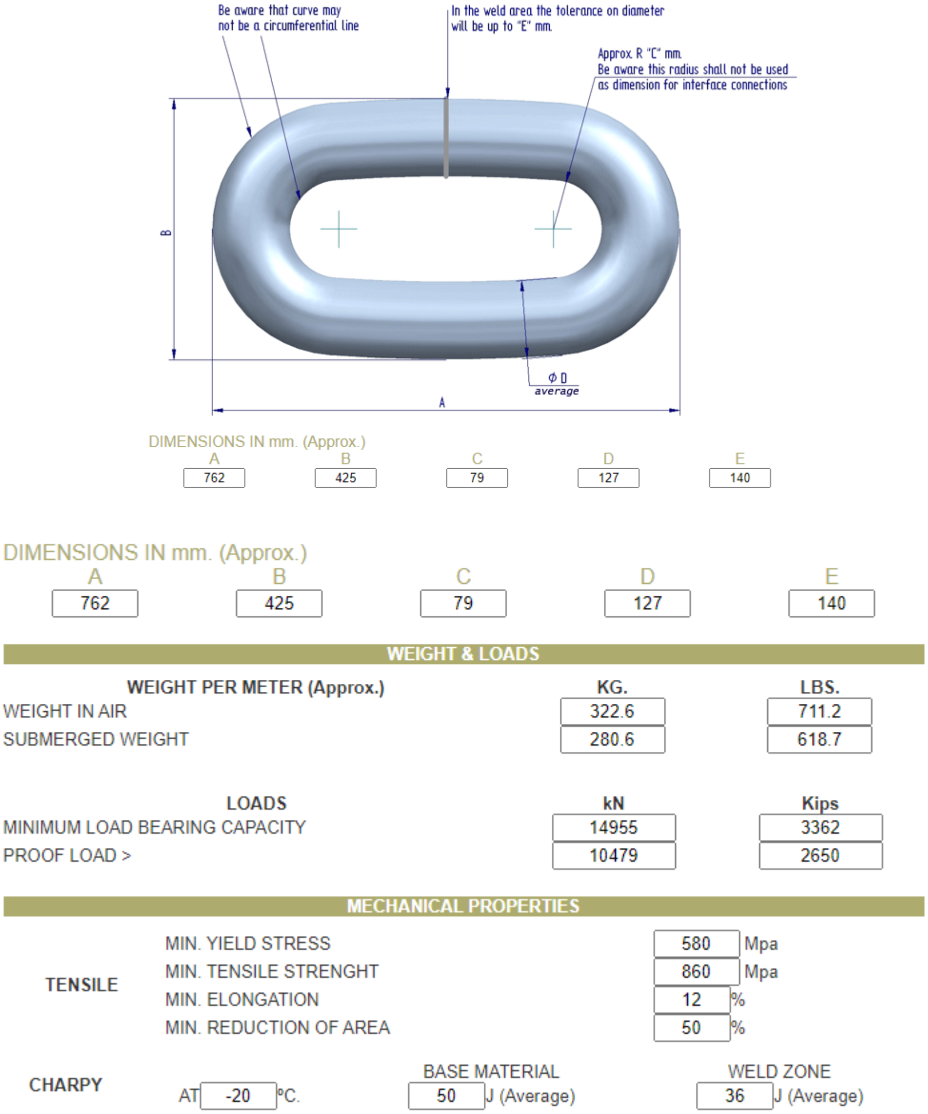
Figure 6.1 Nominal dimension of a chain link and fatigue failure location under tensile loading [p. 10]

Mooring chain have high yield strength compared to other low alloy carbon steel. Yielding due to this load cause a shakedown that prevent elongation of the chain by ratcheting under cyclic loading in service. Under proof loading mooring chain experience compressive residual stresses at the K_t region du to yielding.

The mechanical properties reported for steel grades R4 measured by different authors and required minimum values by Offshore Standard DNV GL -OS-E302 [4] and manufactured by Vicinay (CADEN AS, S.A) [16], tabulated in Table 6.1. and figure 6.2.

Table 6.1. Mechanical properties of mooring chain from the literature and minimum values by DNV GL-OS-E302 [4, 16]

Material grade	$\sigma^{Y}_{0.2\%}\ [MPa]$	$\sigma^{U}\ [MPa]$	$\sigma^{Y}_{min}\ [MPa]$	$\sigma^{U}_{min}\ [MPa]$	$\varepsilon f\%$
R4	896	959	580	860	12



DIMENSIONS IN mm. (Approx.)

A	B	C	D	E
762	425	79	127	140

DIMENSIONS IN mm. (Approx.)

A	B	C	D	E
762	425	79	127	140

WEIGHT & LOADS

WEIGHT PER METER (Approx.)	KG.	LBS.
WEIGHT IN AIR	322.6	711.2
SUBMERGED WEIGHT	280.6	618.7

LOADS	kN	Kips
MINIMUM LOAD BEARING CAPACITY	14955	3362
PROOF LOAD >	10479	2650

MECHANICAL PROPERTIES

TENSILE	MIN. YIELD STRESS	580	Mpa
	MIN. TENSILE STRENGHT	860	Mpa
	MIN. ELONGATION	12	%
	MIN. REDUCTION OF AREA	50	%

		BASE MATERIAL	WELD ZONE
CHARPY	AT -20 ºC.	50 J (Average)	36 J (Average)

Figure 6.2. Mechanical properties of mooring chain [16]

The nominal dimension of the chain is given as a function of the diameter, as shows in figure 6.1. This figure illustrates the fatigue failure locations of the chains under tension loading as well. At both location Stress Concentration Factors take high values, approximately value of 4 [10].

In this study chain size with a diameter of 127mm has been considered. Table 6.2 presents the value of the Proof Load and Minimum Breaking Load (MBL) for the diameter 127mm.

Table 6.2. Minimum breaking loading and proof load for a 127 mm [4, 19]

Diameter (mm)	Material grade	Proof loading [kN]	Minimum Breaking Loading (MBL) [kN]	Nominal stress under tension MBL [MPa]
127	R4	10479	14955	590.3

6.2 Modelling an FE-Model in ABAQUS

The first part of the computational design methods is the mechanical analysis. The first operation within this part is the simplified modelling of the mooring chain to predict residual stresses Finite Element Analysis (FEA) have been employed to simulate the Proof load and service loading under tensile loading model. ABAQUS CAE have been used to compute the simulation.

6.2.1 Model Geometry

An important characteristic of this model is the formulation of the contact between chain links. From a physical point of view, when contact take place, a normal force to the surface of contact and the shear force are transmitted. The contact pressure between the contact surface is defined as a function of the penetration distance between the contact surfaces. Hard contact definition has been chosen, is does not allow the transfer of tensile stress across the interface nor penetration between contact surfaces. It has been enforced using penalty method, which allows some small penetration, consequently improving the convergence rate. Moreover, the penetration distance is generally negligible [10].

Shear forces is defined by the frictional model. Friction between chain links has been modelled. Experiments have illustrated that friction coefficient μ is close to 0.3 in salt water and 0.5 in air. A friction of 0.3 has used in this study.

The geometry has been meshed with 3D solid linear elements with reduced interaction (C3D8R). Two chain links accounting one symmetry plan, with loading model account for combined non-linear hardening.

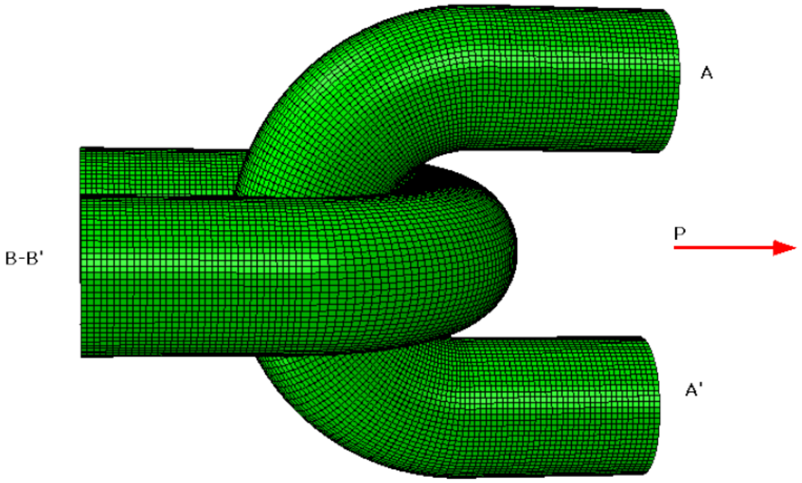


Figure 6.3. Geometry and boundary condition of FEA model

6.2.2 Material's Behavior

The material was assumed to be elastic plastic, with linear isotropic work hardening. The yield stress values of the materials were not chosen to be equal to the minimum specification, but to be more representative of real values issued from tensile tests. In the plastic behavior assumed, the flow stress increase linearly from the yield stress to the UTS of the material, and constant when the plastic strain is above the minimum elongation specified for grade [10, 11]. Because of the large deformation due to compression in the contact zone, the stress-strain data were converted into true stress-true strain. Similarly, the non-linear geometry option of the FEA software was used, and the geometry of the link was updated during each calculation increment [10, 11]. Different models for predicting residual stresses in mooring chains can be found in the literature. Proof load considered as source of residual stresses. Mooring chain manufacturing involves several steps during which residual stresses are generated due to non-homogenous strains or thermal gradients. Residual stress prediction simulates by the tensile loading model.

6.2.3 Boundary condition

The model predicts the final residual stresses field after Proof loading and the stabilized stress cycle when service loading is applied. The material behaviors were modelled as elastic-plastic with the linear isotropic work hardening. The yield surface is given by Von Mises equivalent stress yield criterion. The geometry of this model is presented in figure 6.3. As illustrated in figure 6.3, the boundary conditions are the following: section B-B' is symmetry boundary conditions, section A-A' are coupled with the reference point P. The displacements of this point are restrained in all the direction except the direction of the applied load. The external loading is applied at reference point P the value of the Proof load is been presented in table 6.2.

6.3 Result

6.3.1 Proof Loading and Residual Stress Distribution

Numerical results show that after applied the Proof load, the chain link present high values of stress. Result show that extensive plastic strain is developed in the whole component due to initial Proof load. Because of this high load, high value of residual stress is observed after load removal [10, 11]. Result from several published paper shown that yielding under tension occurs in the region K_t and crown [10, 11]. These are the locations where fatigue failure take place. In addition, residual stresses are more compressive at K_t point than the crown.

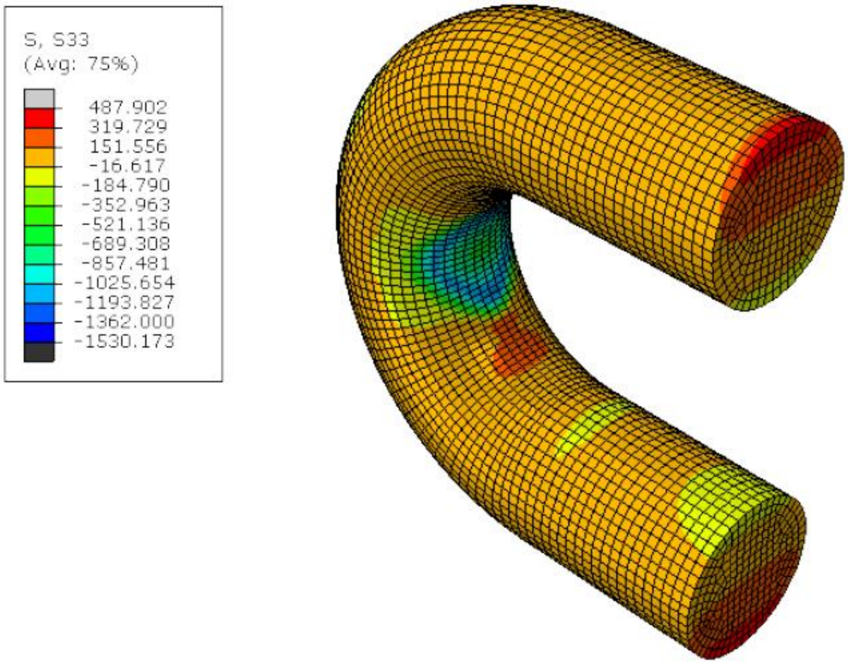


Figure 6.4. Axial stress after unloading from the Proof load, showing region (K_t).

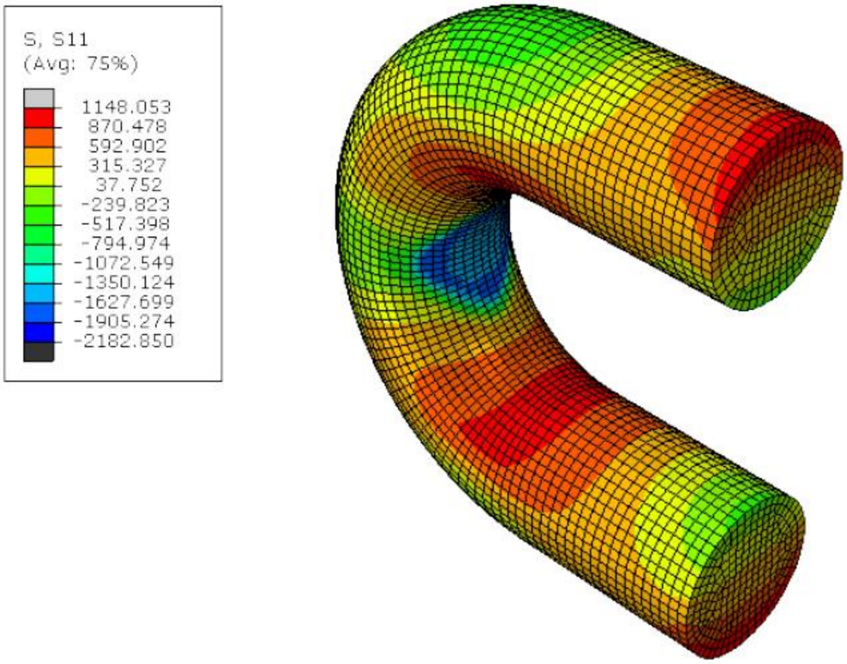


Figure 6.5. Hoop stresses at the crown after unloading.

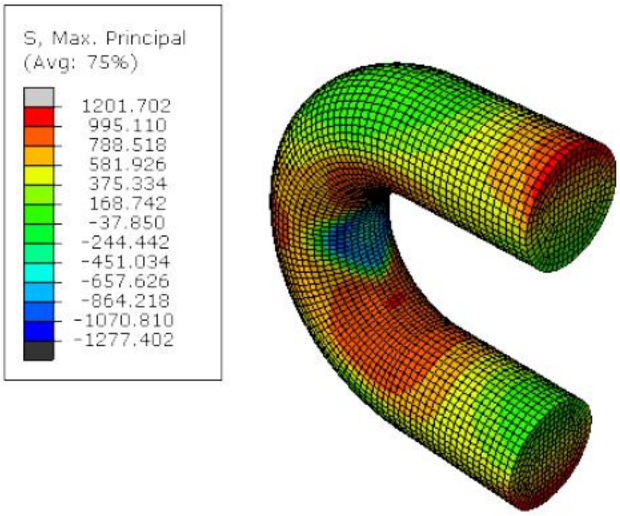


Figure 6.6. Maximum principal stress in the contact zone area after unloading from the proof loading.

Table 6.3. Residual Stress after release of proof load obtained from the case analysed.

		Residual Stress [MPa]	
Link (mm)	Grade		
Region		1	2
127	R4	-184	-794

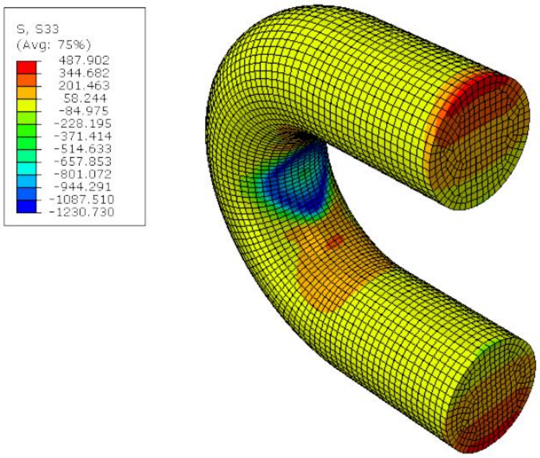
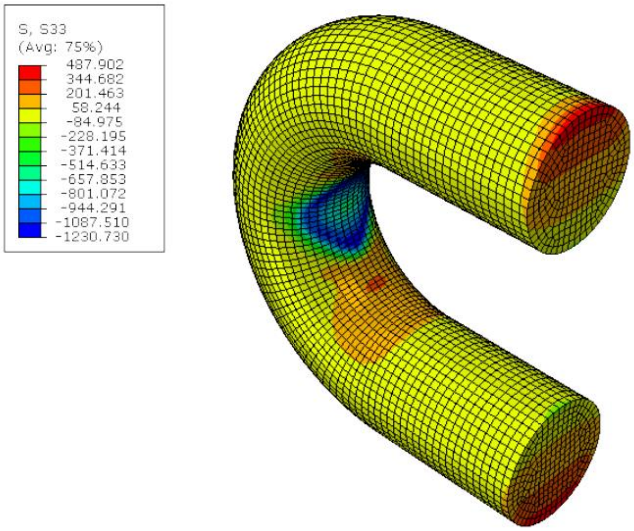


Figure 6.7. Axial stress in region 1 at 10% of MBL.



Figurer. 6.8. Axial stress in region 1 at 20% of MBL.

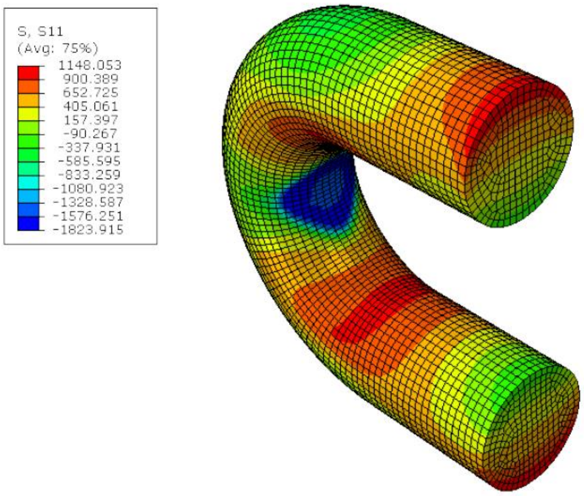


Figure 6.9. Stresses in direction X in regions 2 at minimum load (10% MBL) for fatigue cycles.

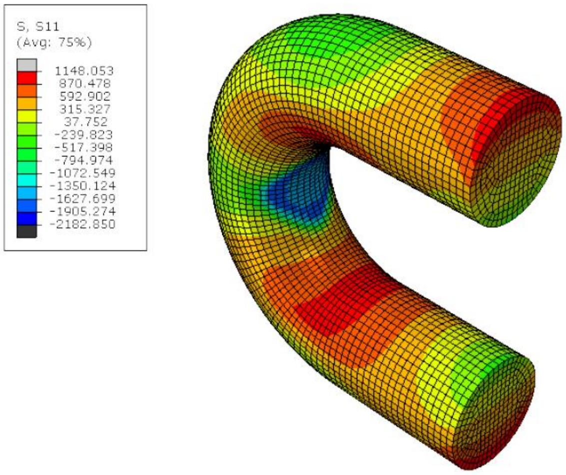


Figure 6.10. Stress in direction X regions 2 at maximum load (20% MBL) of the fatigue cycle.

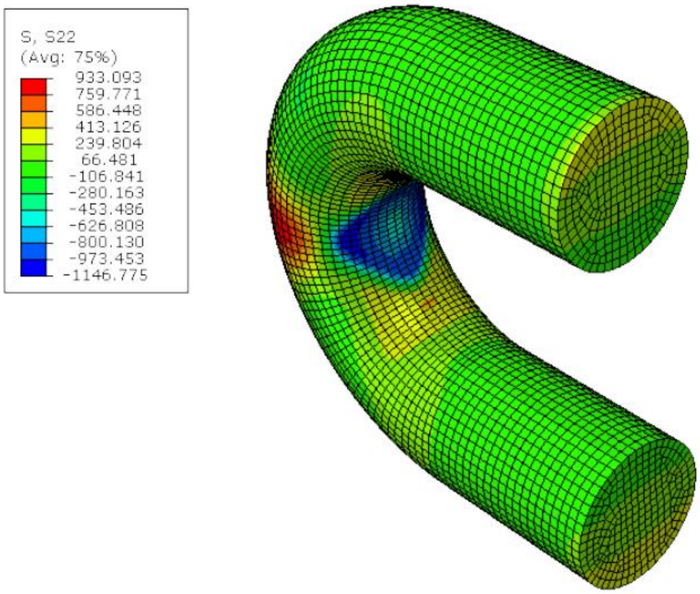


Figure 6.11. Stress in direction Y in contact zone at the minimum load (10% MBL) of the fatigue cycle.

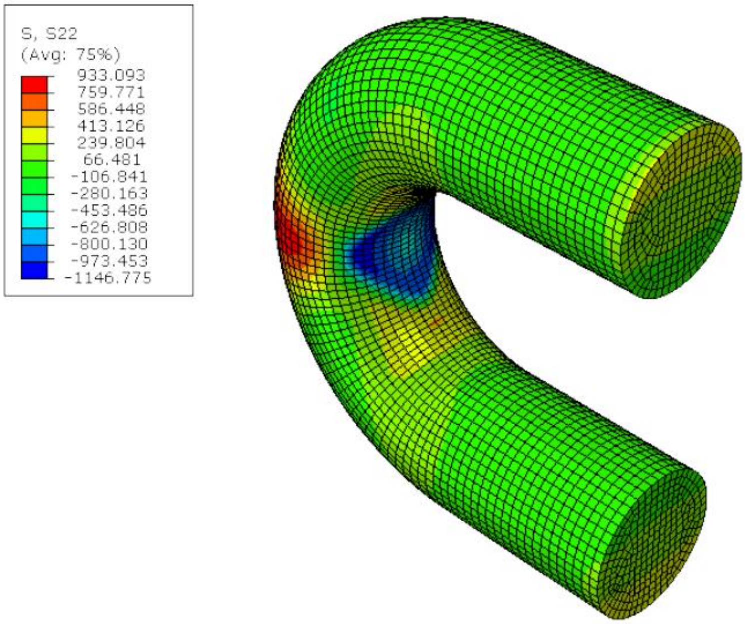


Figure 6.12. Stress in direction Y in contact zone at the maximum load (20% MBL) of the fatigue cycle.

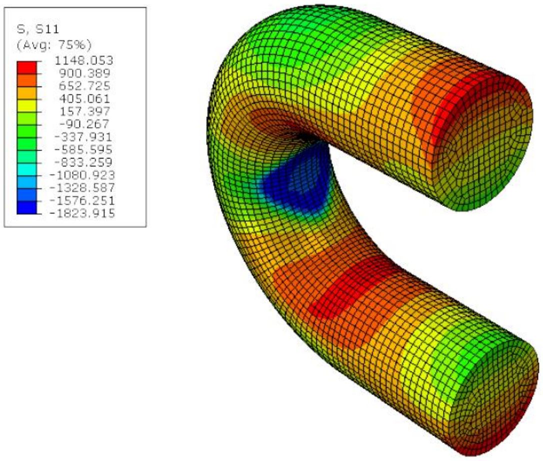


Figure 6.13. Stress in direction X in contact zone at minimum load (10% MBL) of the fatigue cycle.

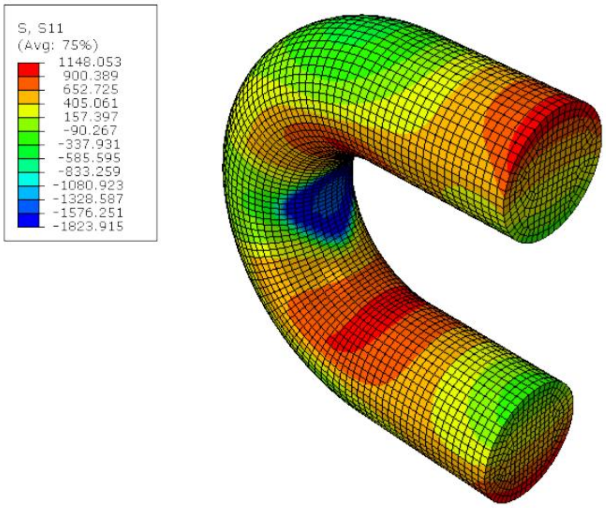


Figure 6.14. Stress in direction X in contact zone at maximum load (20%) of the fatigue cycle

For fatigue stress range the minimum load of the fatigue cycle was assumed to be 10% of MBL (static). The maximum load was assumed to be 20% of MBL. The stress contour plots for each case are shown in figure 6.7 to 6.10 and the stress values after proof loading reported in Table 6.4

Table .6.4. Stress at K_t and crown for 10% MBL and 20% MBL for corresponding stress range

Case	Region	Stress at 10% MBL [MPa]	Stress at 20% MBL [MPa]	Stress range [MPa]	Tensile part [MPa]
127	1	201	201	0	0
	2	-585	-794	209	209

6.3.2 Fatigue Life

Residual stress prediction is followed by the analysis of service loading, it is the last stage of the mechanical analysis. The aim of this analysis is to derive the asymptotic response of the chain links and characterized by a periodic function. It has been referred as a percentage of the Minimum Breaking Load (MBL) of the chain, reported in table 6.4.

The API RP 2SK [22] recommended practice is based on T-N curve (tension number of cycles), that is usually used to predict the fatigue life of mooring component. This methodology is exclusively based on the load applied to the component and does not consider the stress-state promoted by the applied load. The DNVGL-OS-E301 [3] Offshore standard, is based on S-N curve, and consider only the nominal stress range. In the S-N curve only external load range and the cross-sectional diameter is considered. For common chain links the parameter and approaches can be found in chapter 4. It is also assumed a cyclic load with a maximum value of 20% of MBL (2991 kN) and a minimum value of 10% of MBL (1495.5 kN). For this condition a S-N fatigue life estimated of (292143) cycles is obtained.

6.3.3 Residual Stress

The result confirms the benefit of proof loading for K_t and crown regions. In these regions the residual stress is predicted to be compressive, which will improve the fatigue life. In the contact zone, the residual stress is tensile and can reach very high value. These residual stress data need to be analyzed together with local stress cycle due to the subsequent cyclic loading.

7 Discussion and conclusion

Offshore mooring lines components experience harsh environmental condition during lifetime. Because of these reasons a properly inspection methods are an importance to avoid incidence, caused by poor conditions. Along the mooring line there are few areas which are candidate for failure. These areas need special attention during inspection. The top end at vessel interface and touch down area at the seabed are most critical location for failure. Splash zone are more potentially for corrosion of chain.

Fatigue failure is one of the critical failure modes of offshore permanent mooring systems. For fatigue analysis of mooring chain links, connecting to chain wheels at fairlead, chain links passing over bending shoes, or chain linkers provide by chain hawse or chain stopper, the effect of the out-of-plane bending (OPB) on the mooring fatigue should be considered. The T-N or S-N approach uses for fatigue design in offshore industry. The fracture mechanic approach usually is more accurate for fatigue life prediction. Crack initiation point of OPB fatigue and tension-tension (TT) fatigue occur in different location in the chain link. In the case of OPB loading the hotspot located in the bend region, close to contact area between the two links, but for TT loading the locations are in the crown and inner bends. Compared with the traditional TT fatigue of mooring chain which has been studies for many years, OPB fatigue is new. The out-of-plane bending mooring chain involves a complex mechanism, that is difficult to determine. Some guidance has been published that recommended and summarize OPB fatigue assessment methodology. The finite element analysis (FEA) can be used to estimate bending stiffness and Stress Concentration Factor (SCF) and OPB hotspot. To obtain stress due to TT, OPB and IPB loadings, stress concentration factor on TT load and OPB interlink moments are be evaluated through FEM calculation. After the FE analysis, it is found that, proof loading generates compressive and tensile stresses. High tensile residual stress at the periphery of the contact zone can be important to fatigue.

Since offshore mooring chain is typically not coated or protected, it is subjected to general corrosion. In design by imposing a wear and corrosion allowance on the chain with some variation of the allowance depending on the design code and the location of the chain, with respect to the water surface and seabed. In addition to corrosion, wear between links can also be an issue when the relative motions between link exceed 0.5 degree (depending on tension level). Typical requirement for wear and corrosion vary between offshore codes and standards and can range from 0.2 mm per year to 0.8 mm per year depending on weather the chain is a static position on the seabed or in the active splash zone area. Depending on the type of corrosion, and location on link, the stress concentration factors to be different from those derived from a pure tensile loading and corrosion could possibly initiate cracks that would accelerate fatigue at the location. Fairlead is an extremely important interface on the anchor leg system as it is one of the regions of high dynamic activity of anchor leg and the behavior of the fairlead can have large impact on the top end of the anchor leg. Connector should be manufacture from the same material as the chain to prevent the connector from becoming an anode for the chain. Connector should be located outside of regions of high relation motion. Shackle and H-link pin should preferably be wedge shaped pins. Wedge shaped pin prevent rotation of pin in the body. All round pin shackles must have very robust antirotating and pin retaining devices.

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