REVIEW OF AVAILABLE MATERIAL ON USABILITY AND SUITABILITY OF HIGH-STRENGTH MOORING CHAIN (PSA)

Usability and suitability of high strength mooring chains

Petroleum Safety Authority Norway

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Objective:

Systematize the available information with respect to high strength mooring chains failures knowledge.

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Table of contents

1 EXECUTIVE SUMMARY

There have been a number of incidents on the Norwegian continental shelf (NCS) with failures in high-strength mooring chains in recent years. The chain failures occurred in mobile offshore units mooring systems with R5 grade chains.

DNV has been contracted by the Petroleum Safety Authority Norway (PSA) to perform a review of available material on usability and suitability of high strength mooring chains. The definition of project scope is further detailed in section 0.

The review is prepared in a three step approach:

1. Collective review- Systematize the available information with respect to high strength mooring chains failures knowledge.
2. Perform a set of workshops with industry players to establish an overview of available information and identify ways to facilitate the safe use of high-strength mooring chains.
3. Prepare a final evaluation review report including the information collected in the workshops and DNV own assessment.

The current report which pertains to step 3-Final evaluation review of available information, presents and comments the most relevant information collected concerning:

- High-strength chain failures- not attributable to previously observed failure mechanisms;
- Previous workshops, public presentations and literature review;
- Workshops performed within the scope of this project;
- Research activities performed;
- Proposed solutions or mitigation actions;
- Ongoing and planned activities;
- Proposed actions: rule changes and research subjects.

Due to the profile of failures observed in high strength mooring chains the scope of work has focused but is not limited to R5 grade used in mobile mooring chains.

Ongoing and proposed rules and regulations changes, and proposed research shall result on the identification of the critical material properties and its limits which will enable the safe use of high strength chains under acceptable handling limitations.

1.1 Observations summary

The current data analysis indicates that the most probable leading failure mechanism affecting high strength chains, is hydrogen embrittlement, and that there are two main factors for the failures observed in high strength chains:

1. Operational factors

   Three main operational factors are considered to determine the fractures occurrence:

   a) **Handling** - Formation of a hardened or plastically deformed surface layer. Impact and wear by contact with different types of surfaces and high surface contact loads create hardened surface layers where cracks can easily initiate. Plastic deformation from wear could also initiate surface cracks.

   b) **Loading** – Exposure to high tension loads can facilitate crack initiation in hardened surface layers and expedite crack growth in existing cracks specially in the presence of hydrogen as facilitated by CP systems.

c) **Hydrogen source** – Hydrogen resulting from CP will facilitate crack growth in susceptible materials, local corrosion may in some cases also contribute to crack growth. The hydrogen embrittlement effect can be exponentiated by application of high tensile loads to the chains.

2. Material factor
   The material susceptibility to hydrogen embrittlement is a major factor. Its criticality depends on the loading levels and amount of exposure to hydrogen. It affects how fast if at all, existing cracks can propagate through the material bulk.

High hardness and deformed microstructures in the surface are likely key factors for the crack initiation. However, it could also be that the susceptibility to hydrogen embrittlement in the bulk (or near surface area) of the material could be of importance to the observed failures, and better resistance to hydrogen embrittlement by the bulk material could act as a second barrier to such failures.

Historical reasons prevent the use of available data to conclude on the R4/R4s chains susceptibility level, see section 7.3, since operational and regulatory changes simultaneous with the introduction of R5 chains imply that these (mainly R5) chains have been exposed to higher loads and corrosion protection currents.

Several mitigation actions have been proposed and are discussed in sections 10 to 12. The currently proposed mitigation actions are focused on the following handling, operation and specification aspects:

1. Avoid surface hardening and damage during onshore/offshore operations.
2. Reduce probability of crack initiation and crack growth rate by removing hydrogen exposure.
3. Material mechanical properties limitations for increased toughness.

In this report several perspectives of possible future investigations are introduced, specially to allow better understanding on how much each of the enumerated factors contribute and are critical to the failures experienced, see section 12. The final conclusion of such investigations shall be Identification of the significant material properties and its limits which will enable the selection of chains capable of safe use under acceptable handling limitations.

2 INTRODUCTION

DNV has been contracted by the Petroleum Safety Authority of Norway (PSA) to perform a review of available material on usability and suitability of high strength mooring chains.

PSA has observed that:

- There have been a number of incidents on the Norwegian continental shelf (NCS) with failures in high-strength mooring chains in recent years.
- These fractures have occurred both in normal operation and during the installation of anchor lines.
- Failures have occurred for different levels of anchor line tension - also for levels that are significantly lower than the breaking limit.
- Examinations and investigations have been carried out. Several explanations for why these failures occur, and possible measures to counteract them, have been launched and published in investigation reports and at seminars.

Against this background, it is intended to collect and make a comprehensive and critical review of available material on the use, properties and suitability of high-strength anchor chain.

DNV has proposed an approach based in 3 sequential steps:

1. Collective review- Systematize the available information with respect to high strength mooring chains failures knowledge.
2. Perform a set of workshops with industry players to identify ways to ensure the safe use of high-strength mooring chains.
3. Prepare a final report including the information collected in the workshops and DNV own assessment.

This report will focus on the study of failures not possible to explain by known failure mechanisms- over-load, or either tension-tension or OPB fatigue- or for which the failure occurred below the design capacity. All these failures occurred with R5 material grade in mobile mooring installations, but the discussions and conclusions shall not be considered limited to this scope of chains, see section 0. Therefore, mobile and permanent moored installations including offshore wind using chains which material properties are equivalent to R4S to R6 shall be expected to benefit from the observations, actions and conclusions presented in this report.

Due to the sensitive character of the information used in this study, some companies are referred to only by their industry role such as “Supplier”.

2.1 Report structure

The report is divided in the following sections:

Section 2.2 - Abbreviations

Definitions and background information are presented regarding subjects referred to in the following sections.

Section 3 - Basis for work

General description of data sources considered in this report.

Section 4 - Workshops and public presentations.

Summary of relevant information obtained from a selection of previous public presentations, the workshop and meetings held within the scope of this project.

Section 5 - Literature review

Summary of relevant information obtained from the set of related scientific publications.

Section 6 – Current legal setting

Summary and comparative analysis of selection of relevant rules and standards.

Section 7 – Summary of failures

Statistical overview of the reported failures considered in this report. Summary of failure reports and relevant observations broken down in crack initiation and crack growth related evidence. Discussion on lower grade chains susceptibility evidence.

Section 8 – Research performed

Description of reported research performed related to high strength chains failures and inspection observations.

Section 9 – Discussion and analysis of collected data

Systematic discussion of the crack initiation and crack growth mechanisms considered to be responsible for the high strength chains failures analysed. Identification of knowledge status and high-level proposal of research and testing program.

Section 10 – Industry suggested action

Summary of actions proposed by several stakeholders in order to minimize the risks of high strength chains failures and future developments.

Section 11 – Ongoing and planned actions and initiatives

Summary of ongoing and planned rules and standards updates, and research activities related to the failures which are the scope of this report, taken by DNV and other stakeholders.

Section 12 – Recommended initiatives

List of main rules updates initiatives that should be taken and description of the research program supporting those initiatives.

Section 13 – Permanent mooring chains

Clarification regarding permanent mooring systems expected exposure to the type of failures discussed in this report.

Section 14 – Final remarks

Conclusive remarks.

2.2 Abbreviations and Definitions

AHV	Anchor handling vessel
AHTS	Anchor Handling Tug Supply vessel
Brittle fracture	The definition of brittle fracture is sometimes different seen from a structural vs materials perspective. From the former a brittle fracture is typically referred to as fracture where the response of the structures does not deviate from a linear elastic response before the fracture. From a materials perspective the definition is often related to the appearance of the fracture surface. Without the presence of hydrogen, a brittle fracture in C-Mn steels is typically classified a cleavage fracture propagation mechanism. Cleavage fracture is typically related to high local stresses in front of a notch or crack. For hydrogen affected fracture the term brittle is more often used to describe a low fracture propagation resistance. Such behavior could however be linked to different materials failure mechanisms. Typically some stress are also required to cause the low resistance hydrogen fracture, however, such crack may also origin from surfaces without special stress concentration factors.
CGR	Crack growth rate
CP	Cathodic Protection, is a technique used to control the corrosion of a metal surface by making it the cathode of an electrochemical cell. Commonly refers to SACP. In what respects this report the major concern is the formation of atomic hydrogen in the cathode surface which may be absorbed by the metallic structure resulting in local embrittled material and increased risk of HISC.
Degradation	Changes in the original condition observed which may imply a reduction of structural capacity.
Failure	In the general sense of the word, a failure is defined as an undesirable event or condition. For purposes of discussion related to failure analysis and prevention, it is a general term used to imply that a component is unable to adequately perform its intended function.
Failure mechanism	The specific series of events that describe both how the damage/ failure was incurred and the resulting consequences. Examples of failure mechanisms include high-temperature creep, hydrogen embrittlement, stress-corrosion cracking, and sulfidation. Failure mechanism describes how damage came to be present. ISO14224 and IEC 60050 define failure mechanism as “a process that leads to failure (fatigue, wear, creep, corrosion, etc.). The process can be physical, mechanical chemical, or a combination thereof.
Failure mode	Description of the physical characteristics of failure observed. For example, intergranular fracture, buckling, transgranular beachmarks, and pits can all be thought of as damage modes. Failure mode describes what damage is present. In fractography referred to as fracture mode: A. Transgranular Fracture by Microvoid Coalescence (Dimple rupture) B. Transgranular fracture by cleavage C. Quasicleavage Fracture (transgranular cleavage + dimple rupture) D. Intergranular Fracture (In some references, striations are also listed)
Failure (root) cause	The fundamental issue that lead to a failure.

Fracture	A fracture is a partial or complete break in the chain link section.
FOW	Floating offshore wind
HB	Brinell hardness scale characterizes the indentation hardness of materials through the scale of penetration of an indenter, loaded on a material test-piece. It is one of several definitions of hardness in materials science. Considers a spherical indenter.
HISC	Hydrogen Induced Stress Cracking In general there are some uncertainties regarding how the HISC mechanism works, and this could possibly depend on both the environment and the materials in question. However, in general the HISC mechanism arise from atomic hydrogen, either present from the manufacturing and or produced at the surface of the material during operation (e.g. from CP) and diffusion into the material, which reduced the resistance to cracking. The actual cracking process is not fully understood, and sometimes it is distinguished between so-called transgranular and intergranular fracture. The transgranular fracture propagates through the grains in the materials. There is some debate whether this occurs via a cleavage or nano-scaled ductile mechanism. The intergranular mechanism is believed to be caused by hydrogen weakening the cohesion at the grain boundaries. Although not a rule without exceptions, intergranular fracture seems to be more prominent in steels with C-Mn steels with higher strength. Often, the reduction in resistance to fracture resistance is more pronounced if the crack propagation occurs by intergranular crack propagation. Another feature with hydrogen assisted cracking is that it often displays a time dependence, and results could be highly dependent on the loading ratio. Lower loading ratios are often seen to be worse. It has been argued that this is due to the need for the hydrogen to diffuse through the material. It is not possible to very clearly define what is considered high and low loading rates as this can depended on the detailed mechanism and prior hydrogen uptake in the material. In case prior degradation of the grain boundaries has occurred, hydrogen assisted cracks may propagate quite rapidly (could be seconds or less). In case the hydrogen degradation requires time for diffusion during the propagation lower loading rates may be required to achieve the full hydrogen degradation to take place. In the latter case loading rates could be more in the range hours to days. There are also examples of hydrogen crack that has propagated very slowly under constant load. The HISC sensitivity typically increases as the strength of the material increases. It is not fully clear if this is related to microstructure or general stress level that can be achieved in the material (or other reasons). However, based on this it is likely that R5 could display lower HISC resistance than R4.
HV	Vickers hardness scale, similar to HB but considering an indenter in the shape of a diamond in the form of a square-based pyramid. Convertible to Brinell hardness through existing conversion tables.
ICCP	Impressed Current Cathodic Protection
K_{IEAC}	Environment assisted cracking stress intensity
MBL	Minimum Breaking Load
MOU	Mobile Offshore Unit
MPM	Most Probable Maximum

MRB	Manufacturing Record Book
MT	Magnetic particle testing
NCS	Norwegian continental shelf
NMA	Norwegian Maritime Authority
PSA / PTIL	Petroleum Safety Authority Norway / Petroleumstilsynet
SACP	Sacrificial Anode Cathodic Protection
Secondary cracking	Secondary cracking typically refers to smaller crack branches from the main crack plane. They are typically seen for brittle cleavage cracks. However, in this case the secondary cracks tend to be transgranular. Secondary cracks of intergranular nature, in case of materials normally displaying dimpled ductile fracture under the same temperature conditions, typically indicate some environmentally driven degradation of the grain boundaries.
SMYS	Specified Minimum Yield Strength
SSRT	Slow Strain Rate Testing. Used to study stress corrosion cracking. It involves a slow dynamic strain applied at constant extension rate in the environment of interest. SSRT testing contributes to a general observation of the sensitivity of a material to degradation due to influence of hydrogen. There is currently no basis to directly conclude if a material is applicable only based on SSRT. Constant tension tests are aimed at estimating the limit in terms of fracture toughness for when a crack may propagate under constant loading. The test could be useful for establishing this limit, however, there are some uncertainties associated with the influence of the initial defect geometry and the pre-loading loading.
Root cause	Also Failure cause, the fundamental issue that lead to a failure
Untempered martensite	It is a strong, hard and brittle material. In the chains observed it is assumed to result from local superficial heating of the quenched and tempered martensite microstructure followed by uncontrolled cooling. Its hydrogen sensitivity is not fully understood but its high hardness facilitates cracking at much lower strains than for the chain base material as highlighted by DNV-RP-B401 2.5.7.
VI	Visual inspection
Z	Tensile test reduction of area (%) of the specimen.

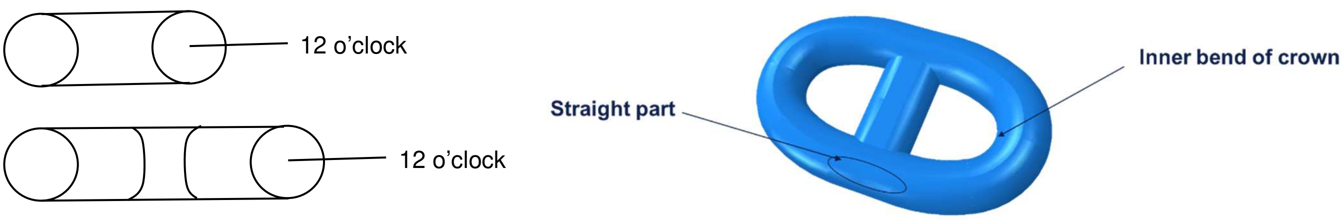


Figure 2-1 Chain notations used in the report.

2.3 Definition of high strength mooring chains

Given that the current observations of the failure data available point out to an important contribution from hydrogen sensitivity, it is proposed to follow DNV-RP-B401 Ch. 2 Sec. 2 [2.5.7] indication that martensitic steels with yield strength above 700 MPa and hardness higher than 350 HV are known to be susceptible to failures due to HISC under CP. Such recommendation includes chain grades R4S, R5, R6 and those chains with equivalent material properties, and are to be considered in this report as corresponding to the high strength mooring chains definition.

2.4 Background information

Following are presented different perspectives of the mobile mooring chains technology which are considered necessary to frame the observations and discussions presented in the remaining report.

2.4.1 Mooring chain lifetime degradation mechanisms

Specifically, on what regards mobile mooring chains in pre-laid systems as most recently used, the following loading types are considered to condition its structural capacity, illustrated in Figure 2-2:

1. Proof load. Performed at manufacturer per DNV-OS-E302 all chain links are exposed to tension loads up to 90% of MBL depending on grade and need to impose plastic deformations to achieve the link specified minimum length. This load is applied without CP.
2. Anchor pre-setting. It is common practice to require up to 450 tonnes which is above 50% of MBL (Ø84 m R5 studded chains), and the minimum load must be applied between 15 and 30 minutes per DNV-RP-E301 and /6/. This operation is performed in general by AHV with ICCP capabilities and with some links over the stern roller, see section 2.4.2. Please see section 8.7 regarding variability of the loads applied in this operation.
3. Mooring line cross tensioning and hook-up. May temporarily induce loads above the specified pretension. Performed under the rig CP.
4. Operational loads. Dominated by fatigue loading centred on the applied pretension. Peak load up to ULS or ALS can be experienced. Chain exposed to rig CP.
5. Anchor retrieval. There is no guidance on maximum load limits. Practical considerations indicate that loads above those used for anchor pre-setting may be required. This operation is performed by an AHV with ICCP capabilities and with some links over the stern roller. Please see section 8.7 regarding variability of the loads applied in this operation.
6. Storage. During storage it is not expected that significant external loads are applied to the chains. Chains stored in flooded chain-lockers are subject to rig or vessel CP which is not controlled and might be an influencing factor. During storing and retrieval operations, including loading/ unloading form the AHV, the chains may be dragged over hard rough surfaces causing drag and wear marks in the straight area at approximately the 1-2 o’clock position.

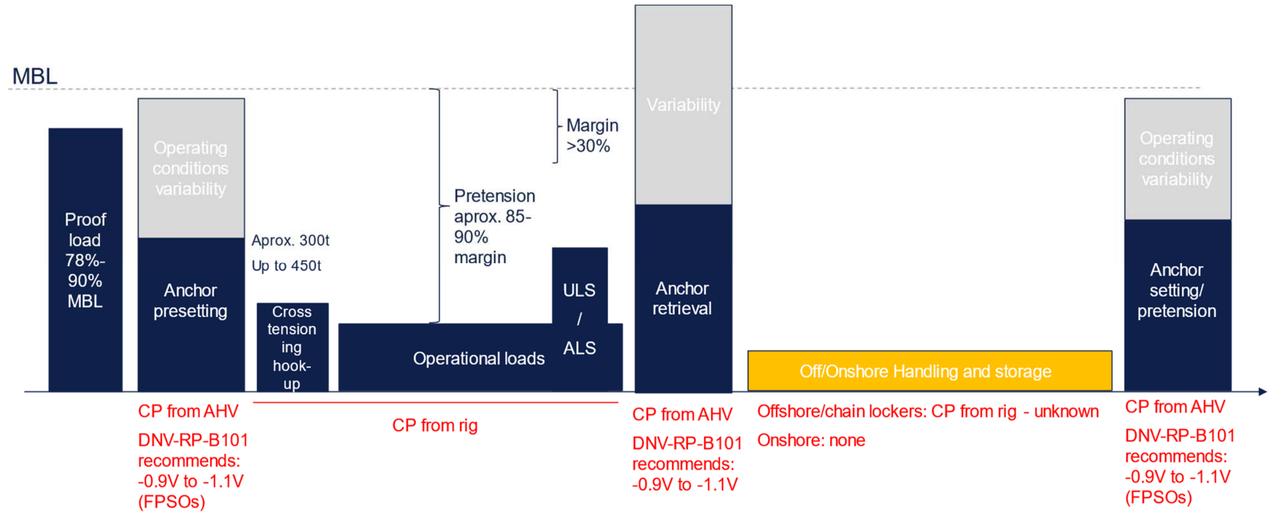


Figure 2-2 Illustration of the different loading levels on a chain lifetime.

2.4.2 Stern roller chain loading

During most anchor setting and retrieval operations the anchor chain is forced to lay on the AHV stern roller as shown in Figure 2-3.

During this operation the following events may occur:

- The chain is subject to very high loads in a configuration (following a curved surface) while it is noted that chain is best suited for direct tension applications where the interlink contact point stresses are not influenced by other induced stresses. E.g. a chain link in a cabelar or fairlead are always accommodated within a groove - hence limiting the external imposed stress in the crown area). As shown, this condition results in very high tensions in an interlink geometry different to that in the tension tests, and to high contact stresses in the straight part of the links.
- Dragging transversally and longitudinally over a hard surface. These events can result in wear and drag marks in the straight part of the links in the 1 to 2 o'clock position.
- The anchor handling vessels are equipped with ICCP systems which may result in very high voltage being applied to the chain links in its vicinity. It is noted that high negative potentials and high loads favour hydrogen embrittlement effects.

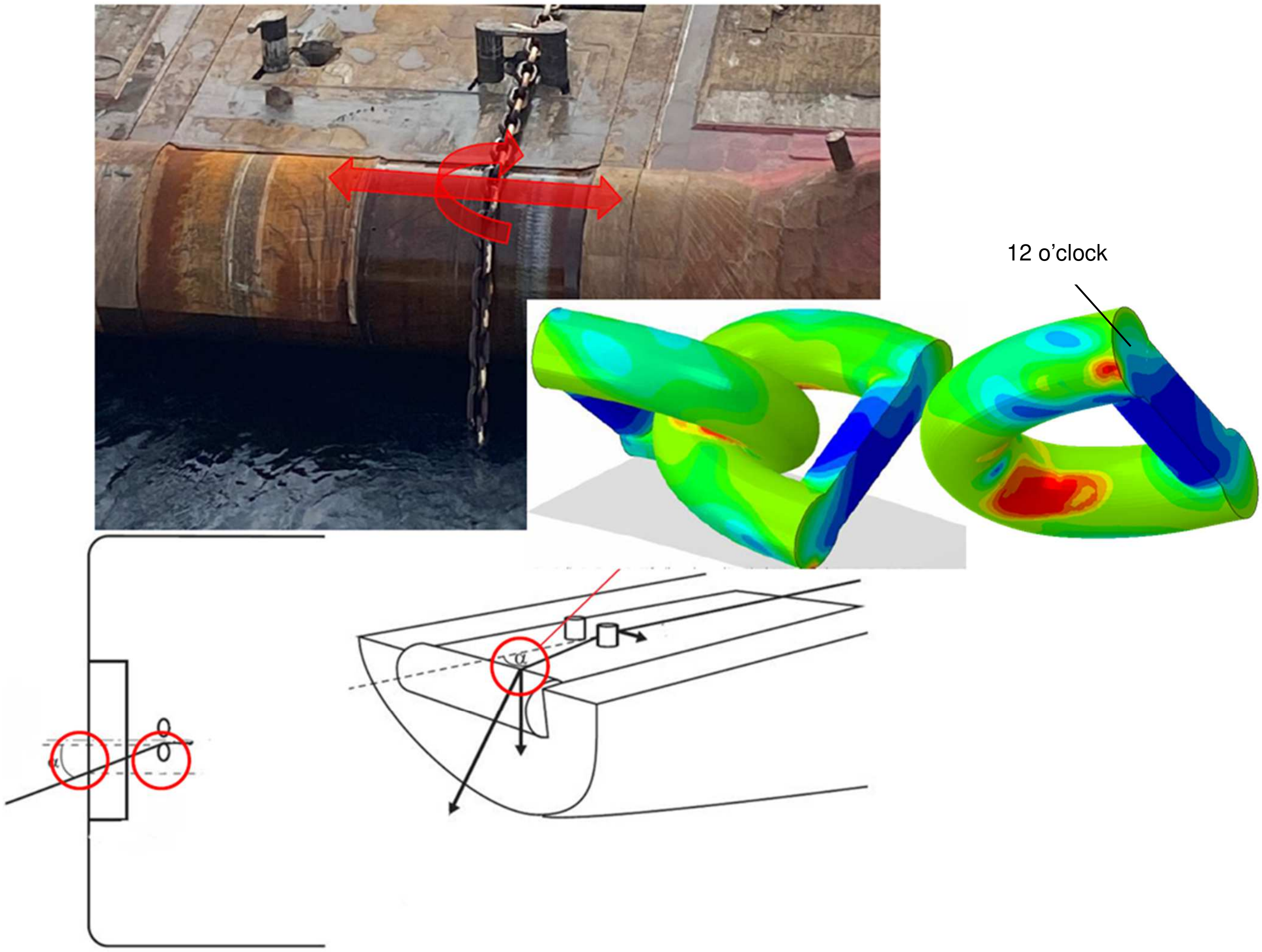


Figure 2-3 Anchor chain over stern roller. Example of Von Mises equivalent stress distribution in chain when tensioned over the stern roller.

2.4.3 Mooring chain link stresses

In order to support the reasoning regarding residual stresses in the crack initiation locations presented in the following section, a specific simplified FEA (Finite Element Analysis) model was prepared.

Two quarter links of studded chain Ø84 R5 were modelled with elasto-plastic material and geometric non-linear conditions.

The proof load was applied and relieved. The resulting residual maximum principal stresses can be observed in Figure 2-4.

For comparison the stress pattern during tensile loading is presented in Figure 2-5 and the stress range for variations between zero and 27% MBL load are presented in Figure 2-6 corresponding to the stress patterns responsible for material fatigue.

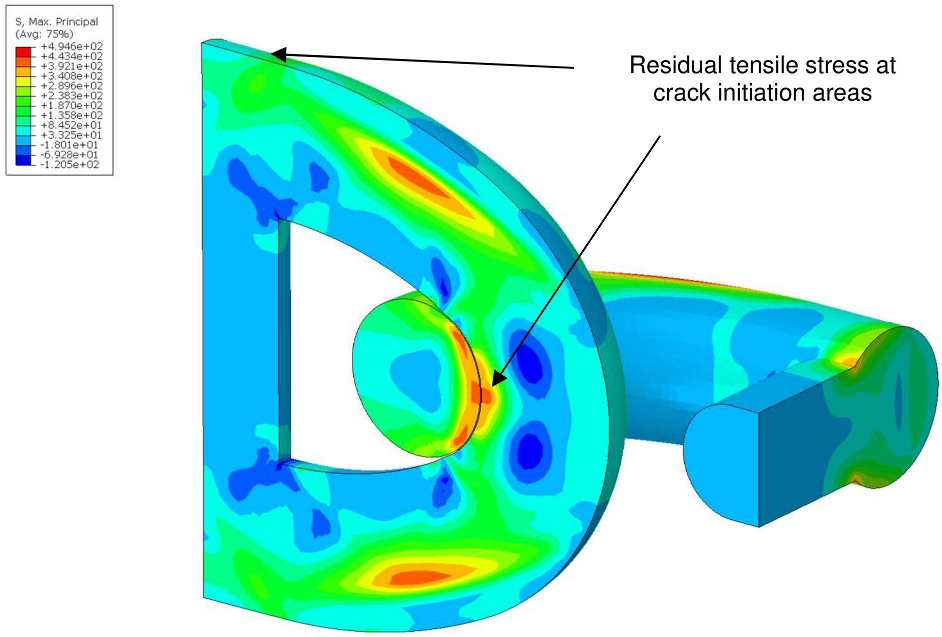


Figure 2-4 Residual stresses at the two crack initiation locations observed in the failure reports

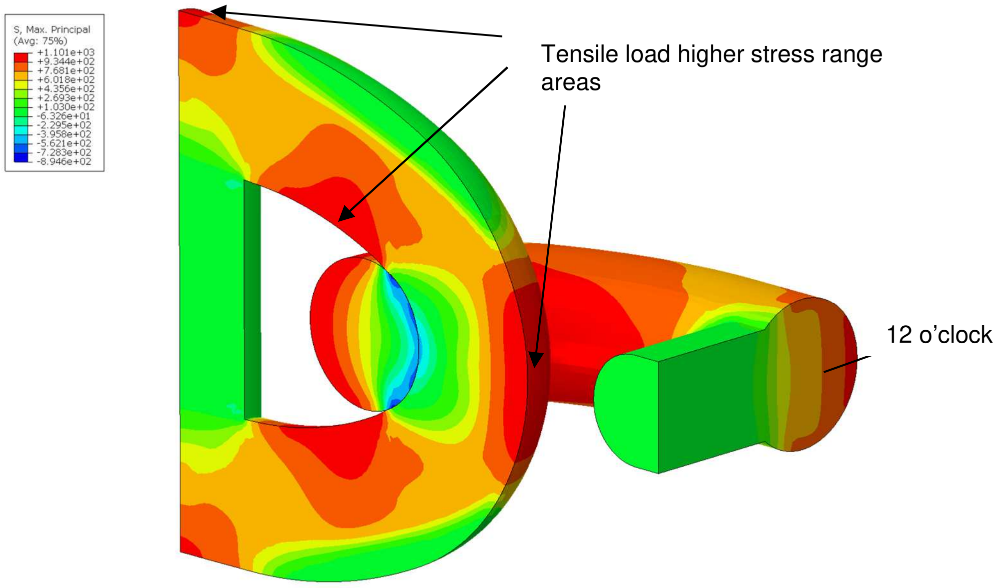


Figure 2-5 Stress concentration areas for the tensile load (75% MBL)

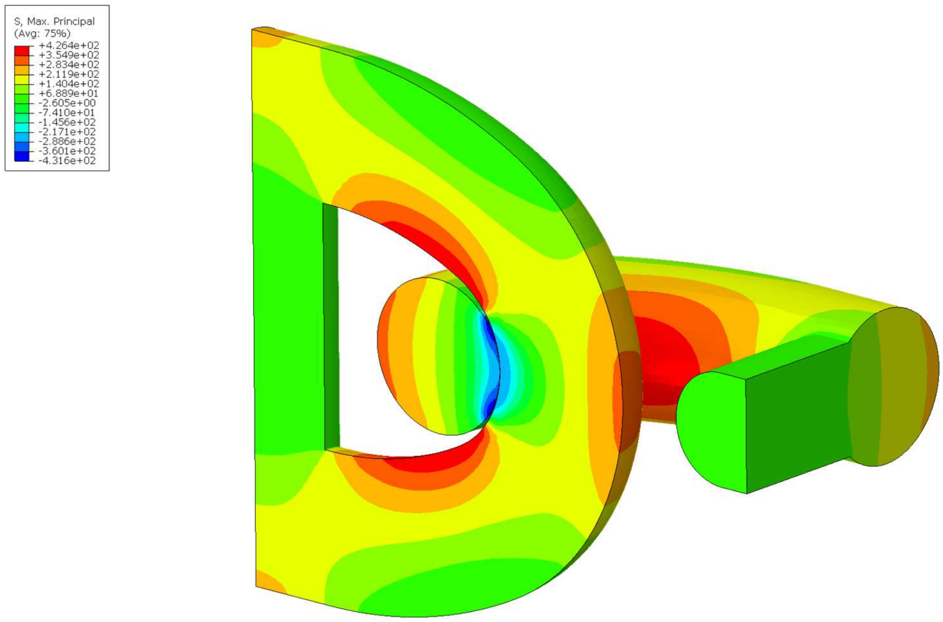


Figure 2-6 Stress concentration areas for fatigue loading range (5 to 28% MBL load range)

3 BASIS FOR WORK

The information presented was collected from different sources:

- High strength mooring chain failure investigations performed by DNV and of which DNV was given due knowledge.
- Investigation and research performed by DNV during the last 2 years.
- Previous workshops
- Available technical presentations by other entities and literature review
- Workshop involving representatives from: Operators, Rig owners, AHV companies, Chain rental companies, Technology providers, Regulatory institution.
- Stakeholders interviews performed within this project scope.

4 WORKSHOPS AND PUBLIC PRESENTATIONS

Information from several workshops and public presentations dedicated to the theme of high-strength mooring chains failures and the respective main conclusions have been collected. Workshops held within the scope of this project are also included and are presented in Table 4-1. The public presentations summary is presented in Table 4-2.

4.1 Previous Workshops

DNV have held non-contractual workshops with industry players prior to the award of this study. This work was undertaken as part of DNV's initiative to try and bring the various stakeholders together in the common challenges with high strength mooring chains.

The workshops have been held individually with three key players in the chain rental industry in Norway and UK, in addition to vendors of anchor handling equipment.

The aim of these workshops was to map today's practise of chain handling and to outline both limitations and potential in equipment currently in use for chain handling, both onshore and offshore.

The workshops were combined with information collected by DNV through meetings and discussion with operators and rig companies in order to map the improvement potential related to current practise and use of equipment.

The outcome was used to calibrate DNV's new requirements to handling of offshore mooring chain, with particular focus on high strength mooring chains. The new DNV requirements are stated in DNV-RU-OU-0300, App. D [1], and were issued in July 2022. These requirements will enter into force on classed units from 1st January 2023.

These requirements with added recommendations and guidance are issued in order to address and reduce the risk of failures associated with chain handling in general and high strength mooring chains specifically. Several obvious actions were required with basis in current knowledge, and these are listed as specific requirements to be complied with in order to hold valid DNV certification on classed units.

Other actions are listed as recommendations, but some of these may be later modified to a clear requirement to be complied with, if ongoing studies should justify such.

The content in DNV-RU-OU-0300, App. D [1] will be further updated based on ongoing studies.

The workshops revealed improvement potential in both equipment and related industry practise, which will also be highlighted as part of the study undertaken for PSA in this report.

4.2 Workshops performed per this project scope

Workshops held within the scope of this project are presented in Table 4-1.

One main workshop was organised including:

- Operators: Equinor, Wintershall Dea, Lundin and Aker BP
- Rig owners: Odfjell Drilling, Trasnocean, Seadrill
- AHV companies: Island Offshore, DOF
- Chain rental companies: IKM, Delmar, Intermoor
- Technology providers: Kongsberg Maritime
- Regulatory and project sponsor: PSA

Follow-up meetings were held with Odfjell and Wintershall, for clarifications of some details.

Specific scope meetings were held with a chain supplier, regulatory entities and a materials science and testing institute.

Most of the comments result in proposed changes to DNV rules for classification and standards, to be implemented or already being implemented as described in the table case by case. Some of the comments are implemented in the proposed test program presented in detail in section 12.2.

4.3 Public presentations

The public presentations summary is presented in Table 4-2. The information discussed is reflected in different forms:

- Establishing a crack initiation and growth assumption as presented in section 7.4
- Research programs presented in section 8.
- Summary of collected data and open items presented in section 9.
- Implemented and ongoing actions and initiatives, and recommended initiatives presented in sections 10 to 12.

Table 4-1 Summary of workshops held within the scope of this project

Date	Participants	Topics and findings	Resulting action
2022-08-18	PSA, Equinor, Wintershall Dea, Lundin, Aker BP, Odfjell Drilling, Transocean, Seadrill, Island Offshore, DOF, IKM, Delmar, Itermoor, Kongsberg Maritime	**Project scope** It is noted that many R4 chains are delivered with mechanical properties complying with R5 and eventually R6 specification.	It is observed that one reported failure occurred in a R4 chain with mechanical properties above those in the R6 scope. Maximum yield strength and yield to strength ratio limitations have been introduced in DNV-OS-E302
		High volume of failures from a specific supplier There is an understanding that one supplier of chains has a significant percentage of the failures detected. Detailed clarification on the differences in productions that could contribute to failure type observed. Such data could also be useful to understand the potential for further improvements from the material side.	It is noted that the referred supplier no longer produces mooring chains. Further investigation indicates that there exists differences of chemical composition and manufacturing procedures which could have contributed to a higher failure rate. Investigation of this is included in the proposed test plan.
		ICCP control and influence Regarding ICCP systems control, monitoring and coverage extension, there are several unknows and uncertainties in these subjects which affect the efficiency and increase the risk of HISC damage to the chains. Monitoring of chains in service was discussed, if there exist equipment that could be installed on chains. Measurements in field with ROV could indicate that current drain increase with increased tension on the mooring line. It was discussed if max. settings could be set for ICCP system in order to protect hull but not get high current drain to chain during anchor handling. Odfjell offered to provide available data to support launch of further studies	Further studies of available data and future chain handling instrumented operations are expected to be performed and possible operations guidelines issued. See notes from meeting with Odfjell drilling and Wintershall Dea.
		It was also observed that high ICCP intensity currents observed when chains are tension might be the source of interlink contact surface heating and influence formation of the local surface high hardness material.	Risk of local interlink heating due to high intensity ICCP current is included in the proposed test plan.

Date	Participants	Topics and findings	Resulting action
		Chain inspection Regarding inspection reports, it was noted that an important amount of data on chain damages found during inspection is available and could be used to improve knowledge of manufacturing and handling damages extent. Considering weld HAZ corrosion line criticality it was noted that currently too many links are discarded due to the corrosion depth being unacceptable defects per the applicable rules. Since no failures have yet been related to such defect, the opportunity to review the criteria was raised.	This topic will be addressed further in a separate study by DNV, to include consideration of statistical data resulting from current surveys.
		Crack initiation conditions It was agreed that a metallographic study of the existing chains with known interlink area cracks should be prioritized. Equinor and IKM offered to provide samples. It was noted that manufacturing marks might also be critical.	Included in proposed test plan.
		Anchor handling loads Load levels, including sampling frequency to record peak loads, under anchor presetting and retrieval was discussed and agreed to be a major concern. It was discussed which level of loads to record and report considering the practical use of the data. This type of data was discussed to be useful to reduce the risk of fatigue failures since this is not covered by the rules for mobile mooring components. In particular, as the pre-set and recovery/"break-out" loads have increased over the last decade and there are now examples from mobile mooring where fatigue have been indicated as the root cause. Considering the loads required for anchor setting, it was noted that the operational profile of the rigs and anchor dragging consequences has changed since inception of the current requirements. It was noted that a revision of the safety factors requirements could be possible. It was also noted the interest in studying the loads on chain wheels, specially associated with possibility to relate to surface damage threshold to be identified by testing. The eventual requirement to define fatigue damage monitoring procedure was discussed upon availability of reliable chain loading during anchor setting and retrieval operations. DNV indicted that some failures have been reported after short service time where fatigue was calculated to have been exhausted due anchor handling operation	DNV is introducing improved load monitoring requirements and post overloading inspection and downgrading criteria. DNV has also started a project to review the operation acceptability criteria with the intention to reduce load peaks.

Date	Participants	Topics and findings	Resulting action
		Future testing priorities Testing/clarification higher priorities discussed: • CP levels to which chains might be exposed when on AHV and from Rig. • Could detrimental hydrogen come from other sources than CP? • Comparing R4 vs R5 base material properties to clarify their hydrogen sensitivity level. Different environments (Salt and H2S), CP exposure and loading. • Criticality of hardened surface layer cracks. It should be confirmed whether there are any other type of defects that can become critical? (Weld defects, weld corrosion line).	Included in proposed test plan
		Hydrogen sources Equinor noted that chaser wires are potential hydrogen sources (ref. also Equinor investigation report).	DNV has introduced a recommendation regarding this issue on DNV-RU-OU-0300, Appendix D 2022.
		Equinor presentation Equinor presented in detail the investigations and conclusions described in Table 4-2. Actions recommendations were also presented as listed in section 10.	
		Delmar presentation Delmar presented its incidents summary where it is noted: - Material found with mechanical strength above R6 specification - HISC failure after exposure to high loads simultaneous with CP Prior to the accident Delmar limited onshore handling yard speed to 5 km/h and uses water irrigation. And limited the planned handling load to 50% MBL. After the incident Delmar has implemented: - ICCP to be switched off during retrieval and installation or to use polyester rope - Reduce weather criteria when it is likely of high loads being experienced. Delmar also proposes: - Alternative anchor recovery methods such as bridle system to be used - Use larger chains with tensile strength below 950 MPa Delmar also presented its anchor retrieval analysis described in section 8.7. Actions recommendations were also presented as listed in section 10.	Conclusions and actions are reflected in updates to DNV-OS-E302, DNV-RU-OU-0300 Appendix D 2022, and proposed research and test program.
		Wintershall presentation Wintershall presented details of a failure investigation included in section 7, referring to an adapter link. A list of actions recommendations was also presented as listed in section 10. ICCP readings performed by Wintershall supported the discussion presented in the specific item above.	Limitations in transition link diameter ratios were introduced ion DNV-OS-E302:2022

Date	Participants	Topics and findings	Resulting action
		Intermoor presentation Intermoor presented details of failure investigations included in section 7 supplemented with Kenter links and swivel failures. Actions recommendations were also presented as reflected in section 10.	Conclusions are reflected in section 7.2
		Odfjell presentation Odfjell presented details of failure investigations included in section 7. A failure due to overload during anchor handling was also reported. High prevalence of failures on chains from one specific supplier was remarked in Odfjell fleet.	Conclusions are reflected in section 7.2. Overloading during anchor handling is addressed in the on-going initiatives presented in section 11.2.
2022-09-02	Odfjell Drilling	Odfjell will secure segments of an R5 chain manufactured in 2008. Availability of samples for future testing is open.	To support identification of material samples for future testing program
		Odfjell provided MRB of R5 chain from 2008 which has not suffered any failure, for DNV to evaluate differences with failed chains	Supported updates to material data interpretation and presentation.
		Odfjell is preparing an ICCP measurement project. The measurement procedure will be sent to DNV for comments. DNV CP expert will eb available for discussions.	Considered as expected future investigations.
2022-09-15	Wintershall Dea	Wintershall presented 3 cases where it was documented an increase of ICCP amperage output when load was applied to the chains. In general it was observed a good control of voltage in the reference cells. DNV highlighted that for hydrogen generation the most important parameter is the polarization potential (voltage). Most positive potential is -0.8 V (Ag/AgCl/seawater) and most negative potential is -1.1 V (Ag/AgCl/seawater) according to recognized standards.	Data to be considered for future ICCP investigations.

Date	Participants	Topics and findings	Resulting action

2022-08-26	Sintef	It was discussed:
		• The importance to determine the difference of R4 vs R5 sensitivity. Compare the fracture toughness (and fatigue) for R4 and R5 bulk material with and without hydrogen exposure.
		• Importance to determine the difference of R4 vs R5 untempered martensite sensitivity.
		  ○ Try to establish untempered martensite with similar hardness as in the mooring chain (500 HV) for R5
		  ○ Use same Gleeble parameters for R4
		  ○ Ideally compare the two materials: hardness, Charpy, fracture toughness, fatigue parameters with and without hydrogen exposure/charging
		• Importance to confirm criticality of existence of the hardened material surface layer;
		• Importance to evaluate role of fatigue mechanisms in initial crack growth.
		• Reproduce deformed surface in the contact zone and perform fatigue testing with and without hydrogen. Analyze for residual stresses
			The conclusions of the discussions are presented in the proposed test plan in section 12.2.

2022-09-02	Sintef	Noted the interest of performing an assessment of the interlink geometry/local stress distribution and residual stresses. 3D scanning of such representative areas should provide important data along with FEA. Sintef demonstrated that crack surface observations alone cannot conclude on brittle/fatigue failure for high strength material. The results from SINTEF indicate that fatigue/cyclic crack propagation can also occur by an intergranular mechanisms. Thus, intergranular fracture surfaces cannot directly rule out cyclic loading. However, as some of the failures has occurred for situations without apparently significant cyclic loading it is still a key hypothesis that sustained crack growth under monotonically increasing or constant loading is the main reason for the larger brittle areas seen in most of the failed links. The basic test scope is proposed to see if this hypothesis could be substantiated. Cyclic loading would be a supplement to compare fracture surfaces. It was concluded that testing should focus on quasi-static loading supplemented by particular cyclic testing.	The conclusions of the discussions are presented in the proposed test plan in section 12.2.

Date	Participants	Topics and findings	Resulting action
2022-10-03	Sintef	A material testing program was discussed in order to clarify the following points: - What is the effective difference between the different grades: R4, R5 (failed chains), R6 and R5 of non-failed chains? - Can the contribution to the observed crack growth in failed chains be clearly distinguished to be due to static or cyclic crack growth?	The conclusions of the discussions are presented in the proposed test plan in section
2022-09-15	NMA	NMA and DNV will discuss further specific rules and standard changes initiatives.	To be further discussed.
2022-10-07	HSE	HSE noted the low usage of high strength mooring chains in North Sea British sector resulting in that no failures have been reported. HSE noted the interest of developing a standard SN curve for high strength chains. HSE offered to support to the detailing of the research and test program.	To be further discussed.

Table 4-2 Summary of main presentations related to high-strength mooring chains failures.

Date	Author/Participants	Topics and findings
2019	Transocean- Jarle Råsberg Intermoor- Lars RuneHelland Equinor- Øystein. Gabrielsen, Linebrudd R5-kjetting- Hendelser, funn og årsaker Ankerhåndteringskonferansen November 2019	Presentation on the following subjects: - Transocean chain failures investigations relating the failures to HISC/Hydrogen - Inspection and repair procedure - Mitigation actions proposed as presented in section 10.3

2020	DNV- Erik Carlberg/Walter Storesund
	R5 Kjettingbrudd- siste års hendelser og aksjoner framover
	Tekna 2020
		Presentationby by DNV of:
		- Failures and characteristics.
		- Suspected causes to failure namely formation of martensite and exposure to CP.
		- Proposed JIP with ABS, “Investigating Mooring Chain Failure Mechanisms and Identifying Possible Updates to Existing Chain Specifications”
		- SSRT and Constant Tension Testing data from Vicinay.
		- Discussion of the chain life cycle phases to be assessed:
		  o Manufacturing
		  o Handling on quay
		  o Anchor handling (load, CP)
		  o Running over windlass and fairlead.

	Equinor- Øystein Gabrielsen
	84mm R5 drilling rig chain breakages- Findings and causes
	Tekna 2020
		Presentation by Equinor in the following subjects:
		- TO Enabler 2019 breakages
		- Crown :
		  o Deformation consistent with stern roller loading
		  o Repeated high loading required- Dynamic pull
		- Side cracks:
		  o Wear marks at approx. 45 deg position on straight part- rough handling
		  o Other indications found on non failed links
		  o High hardness detected in near surface untempered martensite at the wear marks- friction heat
		  o Crack initiation at high load with increased risk due to CP
		- Crack growth investigation
		  o Base material according to specification DNV-OS-E302 with excellent fatigue capacity
		  o Actual breakages: Fast crack growth / “brittle”
		  o Some cracks have stopped growing
		  o Fatigue testing of chain with crown plastic deformation shows longer life than DNV-OS-E301.
		- Hydrogen assisted
		  o Intergranular cracking consistent with HISC
		  o ICCP reading of 16V/60A during anchor handling on chain in water
		  o Case of single brittle fracture on the straight side of link during anchor handling.

2021	DNV- Erik Carlberg R5- a summary of recent years experience Ankerhåndteringskonferansen 2021	Presentation by DNV of internal task force mandate and investigations: - Overview of failures characteristics - Weld line indications. Detectable and removable - Cracks under stud. No impact on fatigue life - Corrosion in weld. May be initiation point for further crack growth - Susceptibility to hydrogen testing. R5 shows higher susceptibility than R4 - Handling marks on yard and stern roller are correlated with observed untempered martensite

<table>
<tr><th>Date</th><th>Author/Participants</th><th>Topics and findings</th></tr>
<tr><td></td><td>Delmar Systems- Hanne Haga
Line failure on 84mm R5 chain during pre-lay
Ankerhåndteringskonferansen 2021</td><td>Presentation by Delmar:
- Link failed in strain zone with 2000 days of use.
- One main overload event with brittle crack propagation
- In or near flash weld
- Additional parallel surface crack detected
- Too extensive corrosion to confirm root cause
- Exposed to CP 16 times during anchor retrieval
- Mitigation actions proposed:
o Turn off ICCP for all chain handling
o Define maximum values for mechanical properties
o More active approach to prevent Hydrogen
o Risk-based inspection interval</td></tr>
<tr><td></td><td>Equinor- Øystein Gabrielsen
Guideline for håndtering og installasjon av (R5) kjetting
Tekna
Ankerhåndteringskonferansen 2021</td><td>Presentation by Equinor on R5 failures characteristics and proposed mitigation actions proposed as further detailed in 2022 presentation</td></tr>
<tr><td>2022</td><td>DNV- Dag-Børre Lillestøl & Delmar-Kai Roger Nilsen
Kjetting- Kartlegging av degradering for å sikre en fortsatt sikker drift.
Tekna DP og forankring av offshore installasjoner 2022</td><td>Presentation by DNV and Delmar of recent investigations and activities:
- Updated overview of failures characteristics and root causes
- Types of degradation- SSRT results show that R5 presents higher susceptibility than R4, propose to introduce operational measures to prevent hydrogen formation due to CP
- Mitigation actions being implemented on:
o DNV-RU-OU-0300 App. D
o Mooring chain inspection regime
o DNV-RP-E301
o GOMO Ch. 11
o DNV-OS-E302
- Sources of hydrogen, failure mechanisms and mitigation actions:
o High loads at installation and over stern roller specifically
- Chain handling offshore- risks due to specific geometric and loading condition
- Metallurgy aspects and DNV-OS-E302 changes
- Inspections and DNV-RU-OU-0300 changes
- Handling requirements and DNV-RU-OU-0300 changes
- Delmar analysis of retrieval operation loading vs wave Hs and direction, and water depth, and payout. Concluded on high potential of ULS being exceeded.
- Focus points & thoughts</td></tr>
<tr><td></td><td>Equinor. Jan Petter Leirvåg, Aage Karl Lambrechts, Øystein Gabrielsen
Hendelser med (R5) kjetting. Veien videre.
Tekna DP og forankring av offshore installasjoner 2022</td><td>Presentation by Equinor with the following main subjects:
- Chain failures 2017-2022 (R5) summary. 10 failures reported.
- Characteristic of failure observed: weld line from existing crack under smeared material, fatigue at crown (low load), fatigue from hardened material near crown center.
- Specifics of R5 failures: crack starting from surface damages, brittle fracture eventually with hydrogen, CP sources in vicinity.
- R4 vs R5: R5 are taken to land every operation, anchor proof load to 100 yrs storm (Ankringsforskriften 09); introduction of ICCP on AHTS.
- Mitigation actions subjects: Change handling of chain onshore and offshore, cut hydrogen, reduce extreme loads in chain, inspection changes.
- Guideline suggestion on handling onshore: See section 10.1.
- Guideline suggestion on operational damage to chains. See section 10.1
- Guideline suggestion on cathodic protection. See section 10.1</td></tr>
<tr><td></td><td>DNV – Dag-Børre Lillestøl
High strength mooring chains – status and actions
FPSO Forum/Mooring Integrity Forum,
Rotterdam, June 2022</td><td>- Updated overview of failures characteristics and root causes
- Background for new DNV requirements to chain handling
- Focus points & risk associated with chain handling
- Current knowledge and practice vs. the required to reduce risk of HISC
- The use of high strength mooring chains vs. Floating Offshore Wind- FOW</td></tr>
</table>

5 LITERATURE REVIEW

The following sources were checked:

- OMAE- ASME database
- FPSO Forums
- Researchgate
- Science Direct

Considering all relevant DNV forensics reports and papers on HISC dating back long before the high strength steels mooring chain became an issue, the most relevant papers identified were:

1. OMAE 2019-95084 Øystein Gabrielsen Inner Bend Cracks in Mooring Chain: Investigation of Cracks Observed on Chains Taken Out of Service.
   It is considered that Øystein Gabrielsen has reflected the conclusions of this paper on his later Tekna presentations.

2. Xutian Xue, Nian-Zhong Chen, Yongchang Pu, Lei Chen, Liang Wang, Fracture mechanics assessment for mooring chain links tensioned over a curved surface, Applied Ocean Research, Volume 117, 2021, 102900, ISSN 0141-1187.
   The paper is based on the mooring line loads in service on a typical semi-submersible and therefore not exactly about what concerns in the project, i.e chain handling conditions. According to the abstract below it is concluded that the tension of chains over an ungrooved curved surface (i.e. stern roller) implies a fatigue life reduction “with the increase of the angle between the transverse axis of mooring chain link and the surface”. It is noted that the angle between the transverse axis of the link (β, Figure 5-1) is low at low tension loads and approximately 90º with high tension loads.

   Abstract: A fracture mechanics (FM) based investigation on the effects of curved surfaces on fatigue lives of mooring chain links tensioned over curved surfaces is conducted in this paper. Three typical curved surfaces including ungrooved surface, shallow grooved surface, and deep grooved surface are investigated. The mooring chain links tensioned over an ungrooved surface are considered under the combined action of in-plane bending (IPB), out-of-plane bending (OPB), torque, and tension. The chain links supported by the bottom of a shallow groove surface are assumed to be influenced by extra IPB. The chain links laying on the upper surface of a deep grooved surface are considered to be subjected to OPB. The results show that fatigue lives of mooring chain links tensioned over the three curved surfaces are significantly shorter than those of mooring chain links subjected to pure tension. Fatigue lives of mooring chain links tensioned over the three curved surfaces would decrease with the decrease of the diameter of the curved surface. For mooring chain links tensioned over an ungrooved surface, the fatigue lives of mooring chain links would decrease with the increase of the angle between the transverse axis of mooring chain link and the surface.

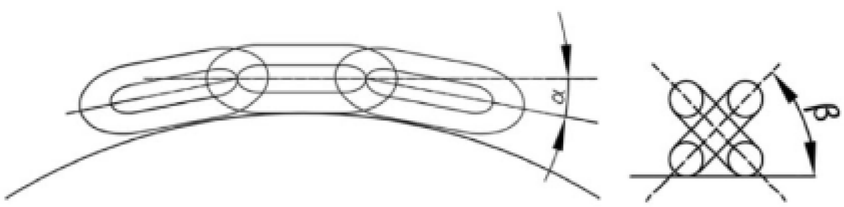


Figure 5-1 Mooring chain over a curved ungrooved surface.

3. HSE, Review of the performance of high strength steels used offshore, prepared by Cranfield University 2003
Determines that steels with YS>600MPa should be examined for the possibility of hydrogen embrittlement noting the susceptibility of high strength steels. It is also considered that CP potentials down to -1,1V can be detrimental in high strength steels and a minimum of -0.85V is indicated as recommended.
it is also noted that sulphides generated by microbial activity in the marine environment can cause a substantial increase in hydrogen uptake by freely corroding and cathodic protected steel.

4. Yan-Lui Zhang, Philip Smedley, 'Fatigue performance of high strength and large diameter mooring chain in seawater', OMAE2019-95984
Finds no difference in the fatigue capacity of R5 versus R4 chains.

5. Artola, G. et al., Hydrogen Embrittlement Susceptibility of R4 and R5 High-Strength Mooring Steels in Cold and Warm Seawater, Metals 2018.
States that high strength steels are more prone to undergo brittle fracture due to interference of diffusible hydrogen with dislocation behaviour. Presents tests showing cumulative detrimental effect of CP and temperature increase in hydrogen susceptibility of R5 material. Results show a notorious impact of CP for overprotection conditions in R5.
Presents arguments for validity of NDT of chains exposed to CP with initiated cracks supporting the effectiveness of the inspection procedures for chains in service, /1/.

6. Zarandi, E. P. and Skallerud, B., Experimental and numerical study of mooring chain residual stresses and implications for fatigue life, International Journal of Fatigue 135, 2020
Measurement of residual stresses in accordance with FEA results.

7. Fernández, J. et al., Fatigue performance of grade R4 and R5 mooring chains in seawater, OMAE2014-23491.
Describes R4 and R5 fatigue test program. Confirms validity of DNV fatigue design curve validity for R5.

Other papers that were observed to include relatable information:

- Zarandi, E. P. and Skallerud, B., Cyclic behavior and strain energy-based fatigue damage analysis of mooring chains high strength steel, Marine Structures 70, 2020
R4 material test program for characterization of cyclic loading behavior. Test data was used to generate numerical model of the material and to estimate fatigue life of specimens reproducing corrosion pitting effects.

6 CURRENT LEGAL SETTING

The following paragraphs present a summary of the main legal requirements on what regards high strength mooring chain supply and anchor lay operations, with focus on the aspects that may influence the chain performance regarding the failures observed:

- Manufacturing specification
- Hydrogen sensitivity
- Anchor installation loads

6.1 Manufacturing

In terms of manufacturing and supply specifications the following standards are analysed:

- IACS W22 Req. 1993/Rev. 6 2016, Offshore Mooring Chain
- DNV-OS-E302, Offshore Mooring Chain
- DNV-CP-0237, Offshore mooring chain and accessories, Approval of Manufacturers

Comparison of the different standards according to the parameters considered to be most influential regarding hydrogen embrittlement are presented in Table 6-1.

Both the IACS W22 and DNV combined OS-E302 and CP-0237 are very similar. It is noted that in excess of IACS W22, DNV requires hardness tests every 100m of produced mooring chain which are to be compared with links used for material testing. While IACS 22 requires in excess of DNV that hot ductility tests be performed.

It is noted that acceptance limits are lacking for some important tests, in all relevant standards and rules, namely:

- SSRT testing
- K_{IEAC} testing

Establishment of the respective limits is included in the objectives of the test program presented in section 12.2

6.2 Hydrogen sensitivity

Considerations regarding hydrogen sensitivity are found in:

- NORSOK Standard M-001:2014, Materials selection
- ISO 21427- Materials selection and corrosion control for oil and gas production systems
- DNV-RP-B101:2021, Corrosion protection of floating production and storage units
- DNV-OS-B401:2021, Cathodic protection design

A summary of the most significant statements are presented in

Table 6-2.

It is noted that two thresholds relative to hydrogen embrittlement of submerged martensitic material parts subject to CP, can be identified in the referenced standards:

- Hardness higher than 332/ 350 HV, depending on the reference
- SMYS above 550 MPa. Above this level CP limitations are defined to avoid detrimental effects per DNV-RP-B101 Table B-1
- Effective yield stress above 900 MPa for welded parts.

These conditions are reflected in the criteria used to define this project scope as presented in section 0.

6.3 Anchor installation loads

The following standards and regulations define anchor installation loads:

- ISO19901-7 (2013) Station keeping systems for floating offshore structures and mobile offshore units
- NMA Regulations of 10 July 2009 No. 998
- DNV-RP-E301:2021, Position mooring

Fluke anchors are the most common solution on mobile mooring installations and common to all the observed failure cases.

The minimum installation tension load is defined with dependencies to the following considerations:

- Existence of other installation in vicinity implying risk of collision upon failure or dragging of anchor;
- Type of soil;
- Possibility of defining a survival (operation) condition on which mooring loads can be limited or the risk resulting from anchor dragging reduced by stopping activities/disconnecting from risers.

In summary:

- Environmental operation limits shall be defined- survival condition.
- The specified anchor installation load corresponds to the maximum environmental loads in the survival condition.
- When anchor dragging may result in critical condition due to other structures in the vicinity, or mooring systems reconfiguration, a 100 year storm check shall be performed.
- Detail calculations of anchor holding resistance defined in DNV-RP-E301 allow for accounting for post-installation soil effects in order to reduce the load required to be applied for installation, depending on the known soli characteristics.

Other considerations that shall also be taken in consideration but are not quantified are winch pull limit and anchor retrieval feasibility.

The definition of installation load hold time of min.15 mins is common to all references.

6.4 In service inspections

The current industry and class regimes are prescriptive and developed without considerations for the current practices of onshore and offshore chain handling nor there are considerations for HISC implications.

Updating of inspection regimes towards a more condition/usage based approach which accounts for overloading and CP exposure events, was introduced with the 2022 Edition of DNV Rules. Further requirements to the inspection regimes are being progressively implemented along with the industry's ability to adopt load cell technology and utilize data processing and presentation of loads during and from operations, as presented in sections 10 through 12.

Table 6-1 High strength chains manufacturing

	IACS W22 Req. 1993/Rev. 6 2016	DNV-OS-E302	DNV-CP-0237
Manufacturing process	-	Ch.2 Sec.1 [1.2.1] The steels shall be manufactured by an electric arc furnace, basic oxygen converter or other approved process. Secondary refining is required. Steel grades R4S, R5 and R6 shall be vacuum degassed. Ch.2 Sec.2 [2.5.1] Grade R4, R4S, R5 and R6 shall be supplied in the quenched and tempered condition. Tempering temperatures shall not be less than 570°C and cooling after tempering shall be in water.	--
Microstructure/ Composition	-	Ch.2 Sec.1 [1.2.2] The steels shall be killed and fine grain treated. The austenite grain size of rolled steel bars, steel forgings and steel castings shall be 6 or finer. The fine grain size requirement shall be deemed to be fulfilled if the steels contain Al, Nb, V or Ti, either singly or in any of specified combinations. I.e. Aluminium content above 0.020%.	
Material examination	2.2.1.3 Similar to DNV	Ch.2 Sec.1 [1.2.3] For steel grades R4S, R5 and R6 provide: a) Each heat shall be examined for non-metallic inclusions. b) A sample from each heat shall be macro etched to be sure there is no injurious segregation or porosity. c) Jominy hardenability data	Sec. 3 [4.2]
Chemical composition	1.5.3 Similar to DNV	Ch.2 Sec.1 [1.3] Steel grades R4, R4S, R5 and R6 shall contain a minimum of 0.20% molybdenum.	Sec. 3 [4.2]

Material testing- rolled bars	2.2.3 Similar to DNV	Ch.2 Sec.1 [1.5.3] Mechanical testing: - Tensile; - Charpy V To comply with Ch.2 Sec.1 [2.5.4] Table 1 Ch.2 Sec.1 [2.6] Grades R3S- R6: Testing for hydrogen embrittlement by SSRT. Ratio of reduction of Z (area ratio) values between samples subject to baking and not, shall not be less than 0.85.	Sec. 3 [4.7] Hydrogen embrittlement
Material testing- final product	-	Ch.2 Sec.2 [2.5.7] Hardness tests every 100m to be compared with links used for material testing.	-
Material testing for Manufacturers Approval	2.2.3.5 Maximum hardness for R5 is HB340	-	Sec. 2 [4.6] Hardness testing along a diameter. The hardness at the centre shall not be less than 85% of the hardness at one-third of the radius from the surface.
	1.3.3 CTOD testing. ISO 15653 @-20degC. Limits per Table. 1.3.5 For R4 and R 5 requests: - Stress corrosion cracking, - Hydrogen embrittlement study- slow strain test pieces in hydrated environments.	-	Sec.2 [4.5] CTOD testing- ISO 12135 @ -20 degC. Limits per Tab. 4 Sec. 2 [4.8] SSRT for R4 and R5 in air and seawater. No criteria. Sec. 2 [4.9] R6- SSRT air and seawater @ -850 mV and -1200 mV. No criteria.
	-	-	Sec. 2 [4.9] R6- KIEAC, per ASTM E1820, seawater @ -950 mV and -1050 mV w/ precharging
	1.3.5 R4 and R5 requirements: - Heat treatment study - Temper embrittlement testing - Strain age testing	-	Sec. 3 [4.3] Heat treatment sensitivity study QT condition Sec. 3 [4.5] Temper embrittlement testing, QT condition Sec. 3 [4.6] Strain age testing- 5% @100degC, 1 hr
	1.3.5 R4 and R5 requirements: - Hot ductility tests	-	-

Table 6-2 Hydrogen sensitivity

	NORSOK M-001	ISO 21427	DNV-RP-B101	DNV-RP-B401
Martensitic materials	6.1 For submerged parts in martensitic carbon materials exposed to CP, the hardness shall be lower than 328 HB (332 HV) or 35 HRC. For submerged carbon or low carbon alloy steels intended for welding, SMYS shall be lower than 900 MPa.	6.9 For submerged components exposed to CP: - Actual yield strength shall be lower than 900 MPa; - Hardness shall be lower than 35 HRC or 328 HB (332 HV)	3.3 CP may induce HISC in extra high strength steels with SMYS > 550 MPa. The applied protection potentials shall be in accordance with (DNV-RP-B101) Table B-1 to avoid any detrimental effects due to hydrogen generated by the CP	2.5.7 For martensitic carbon, low-alloy steel, failures caused by CP induced HISC have been encountered involving materials with an actual YS and hardness of about 700 MPa and 350 HV respectively.
Untempered martensite	-	-	-	2.5.7 It is widely recognized that untempered martensite is especially prone to HISC. The welding of materials susceptible to martensite formation should be followed by post weld heat treatment (PWHT) to reduce the heat-affected zone (HAZ) hardness and residual stresses from welding.

Line tension limit- Design safety factor, ULS & SLS	10.2 MBL safety (Quasi-static/Dynamic analysis) Intact: 2,00 / 1,67 Redundancy check: 1,43/1,25 Transient: 1,05 B.2.3.11 Only Dynamic analysis (100 years) Consequence Class 3/2/1 Intact: 1,9/1,8/1,5 1 line fail: 1,3/1,2/1,1	Section 14 In addition to ISO B2: consider operation condition with consequence class 3. - units close to another, consider 2 line break, 10 yr/max. Operation condition	5.3.1 Design line tension T(d) calculated per DNV-OS-E301 Ch.2 Sec.2 [4.2.1] 5.3.2 Consequence class 1 and 2	-
Test load	10.4.6.3 Winch load Larger than design extreme tensions intact- SLS design situation Larger than design mean line intact – ULS design situation, other installations in vicinity. 15 minutes	Section 17 May reduce from ISO 19901-7 B2.3.8, to: - measured at dip-down point is larger than maximum line dynamic analysis survival intact condition. Interrupt operation if load above: - tested hold load (no other installation in vicinity) - 80% tested hold load (other installations in vicinity)	5.4 Minimum installation at dip down point T(i)= T(d)- post-installation effects	Ch.2 Sec.4 [3.5.1] With anchor drag: anchor installation tension at the dip-down point not less than the maximum line tension caused by an environment load corresponding to the maximum operation condition, intact mooring. [3.5.3] Without anchor dragging possible: Use a tension according to ULS/ALS requirements (100yrs).

7 SUMMARY OF FAILURES

The information available on the reported chain failures is presented in this section, first by a purely statistical summary and in sequence by extracting the significant observations regarding crack initiation and crack growth evidence.

7.1 Available failure cases data analysis

From 18 failures of R5 chains that have been communicated to DNV from 2015 to 2022, a breakdown of the main characteristics is presented in the following tables. Cracks detected in the chain neighbouring links after the failure are not counted.

It is noted that all failures occurred in mobile offshore units mooring systems.

One failure on a R4 chain was attributed to hydrogen embrittlement in 2012, but the failed chain presented mechanical properties above R5 requirements. Considering that a specific manufacturing anomaly is responsible for this failure, it will not be included in the following statistics.

Table 7-1 Reported and known failures per chain classification society

Classification society	Number of events	Comments
DNV	13	Preponderance due to that non-DNV class installations are not required to report to DNV
ABS	5	

Table 7-2 Reported and known failures per chain type

Chain type	Number of events	Comments
84 mm R5 Stud	10	
76 mm R5 Stud	1	
84 to 104 mm R5 adaptor	2	
R5, unknown diameter	5	Cases not fully reported to DNV

Table 7-3 Failure life phase

Phase of failure detection	Number of events
Operation	11
Hoisting out of chain locker	1
Pre-setting	4
Retrieval	1
Unknown	1

A global summary of failures data is presented in Table 7-4. Due to extensive corrosion in the crack surface, it is not possible to clearly confirm in a significant amount of cases, if there was a fatigue phase in the crack growth and such cases are marked with a question mark. There is one confirmed case of mixed brittle and fatigue crack growth phases, case 8.

Table 7-4 Main failure summary as described by the different investigation reports

		Crack location			Crack initiation			Fracture mechanism						
	No report	Crown	Straight	Weld line (or near)	Weld defects	Detected untempered martensite	High contact loads/ wear area	Brittle	Fatigue	Reported HISC suspected	Chain age [yr.]	Load / MBL	Phase of failure	Distance to vessel at failure
1	x												Operation	
2			x			x	?	x		?	<1	31 %	Operation	200 m
3	x		x			x	x	?	?			21 %	Pre-lay	20m at accid. Previous 100-200m.
4				x	x			x				29 %	Operation	500m
5	x												Operation	
6		x					x	x		x	6		Operation	Seabed
7		x					x	x		x	6		Retrieval	Seabed
8			x			x	x	x	x	x	5		Operation	
9	x												Operation	
10		x (4x)					x	x	?	x			Hoisting out of	Locker
11		x (4x)					x	x		x	1		Operation	590 to 1712 m
12				x				?	?		5	18 %	Operation	Seabed
13			x				x		x		7	7 %	Presetting	
14				x	x	x	x	x		x	8	44 %	Presetting	
15	x							x					Presetting (?)	
16		x					x	x		x	7		Operation	Below fiber rope
17		x					?	?	?		7			
18	x	x-out							x		7		Operation	Bottom chain
	5	**7**	**4**	**3**	**2**	**4**	**12**	**13**	**7**	**9**				

Comments:

(1) (4x) indicates that four other neighbouring links were found with significant cracks after retrieval.

(2) All crown cracks start from the inside or near inside of the bend area, except case 18 for which there is no report yet

(3) Straight area cracks occurred in both the weld and opposite side and started outside or near outside area.

(4) Crack surface corrosion doesn't allow identification of failure mechanism in many cases which doesn't allow to conclude on the existence of fatigue phases.

(5) Also note that the most recent failures are still under investigation, therefore the root causes and mechanisms are not fully declared.

The failure data is further segregated to relate the failure mechanism with the location of crack in Table 7-5. The uncertain cases are represented by numbers inside parenthesis.

The existence of drag wear marks in the vicinity of crack initiation of failures at the straight part of the link is to be noted.

It is also noted that all crown crack initiation is related to visible interlink contact and wear dents. The dents are visibly off-centre denoting high loading conditions with the chain bent such as while being pulled over the stern roller, see section 7.2.

Table 7-5 Combination of failure mechanism and crack location. Values in parenthesis denote uncertain cases)

	Weld line	Straight (not- weld)	Crown
Mechanism			
Fatigue	1	2 (+1)	1 (+2)
Brittle	2 (+1)	2 (+1)	5 (+1)
Fatigue + Brittle			1 (+2)
Root cause			
Interlink contact or wear marks			5 (+1)
Drag wear marks		3 (+1)	
Untempered martensite	1	3	
Weld defects	2		

The reported load level at failure, see Figure 7-1, can only be taken as indicative since in most cases the instrumentation is not reliable, specially loads in chain handling which are taken from bollard-pull settings.

The reported cases occurred all at relatively low loads.

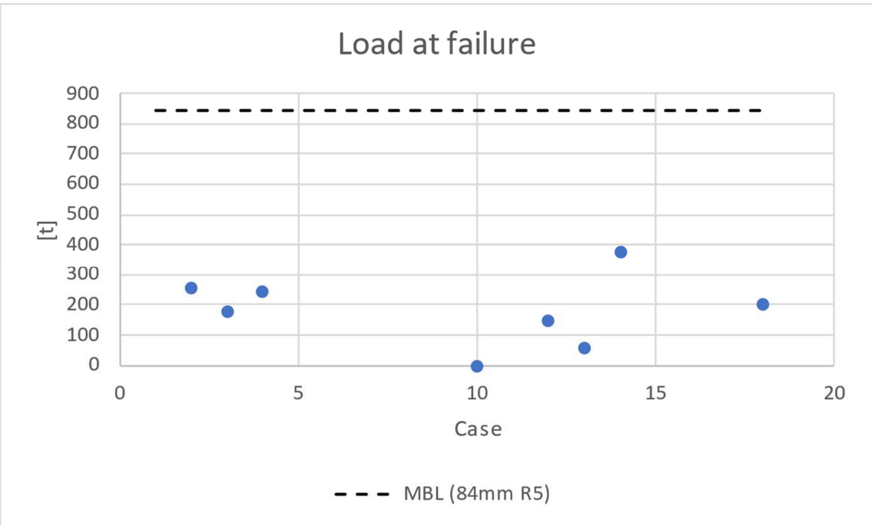


Figure 7-1 Known chain load at failure

The age of the chains at failure is represented in Figure 7-2. Given the intermittent use of mobile mooring chains which correspond to the totality of the reported failures, this parameter does not represent an actual service time.

It is noted that the collected data suffers from some bias in that there is a preponderance of DNV classed chains and rigs due to failure reporting requirements of classed items. The high percentage of Ø84mm R5 chains from a specific supplier in production for the Norwegian continental shelf can also be a factor. It was not possible to obtain a full survey of the produced chains from all the suppliers. From the 18 reports considered, 13 are from that supplier, 2 from another supplier, 1 from a third supplier and 2 of unknown supplier.

It is noted that most of the failures result from the 2013-2015 production. From 2015 from which 5 failures resulted, it shall be noted that 2 are related to oversized adaptor links. This leaves 3 failures due to material fault in 2015 for which the production level was apparently low (according to certification activity) and before a period without production (2016), which may indicate manufacturing difficulties.

This observation leads to suggest a specific comparative investigation of the fracture mechanics and hydrogen sensitivity properties between chains from different suppliers.

The cases with chains with very little use are highlighted, indicating the potential for very fast crack growth in both the straight and crown areas:

- In one case occurring in 1 year old chain, the failure was at the straight part with friction marks and detectable untempered martensite.
- The other case with 1 year old chain occurred in the crown and is most likely hydrogen induced cracking. The main failed link was located above the cable lifter and at least 3 other neighbouring links had detectable cracks in the same area. The failure occurred during chain handling.

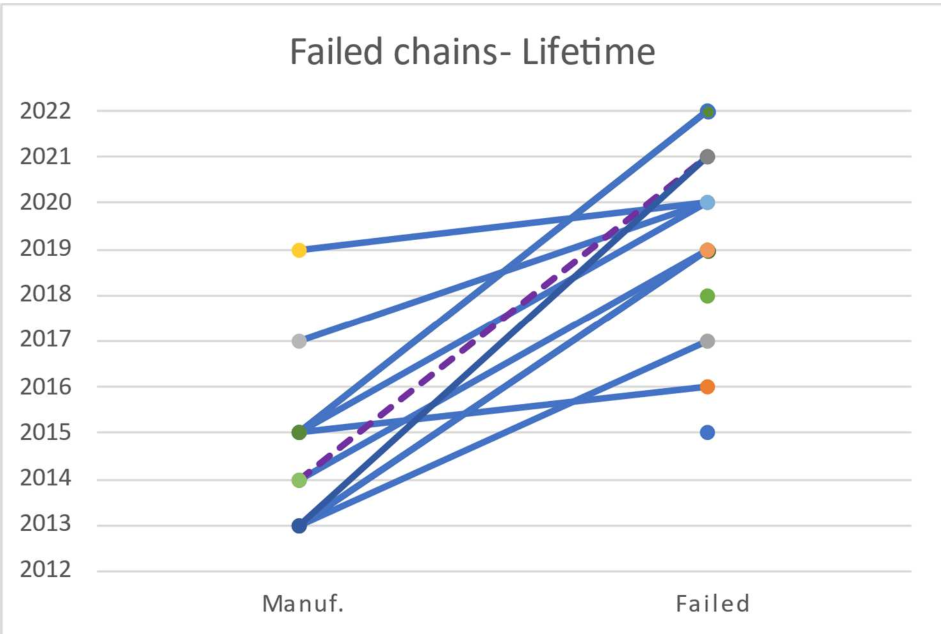


Figure 7-2 Failed links lifetime representation. Thirteen full date pairs available.

The mechanical properties of the chain links reported in the failure investigation reports are presented in Figure 7-3. The R5 yield and tensile strength limits per DNV-OS-E302 are also presented along with the DNV-RP-B101 HISC awareness limit of 550 MPa Yield strength limit. All chains comply with the R5 definition limits.

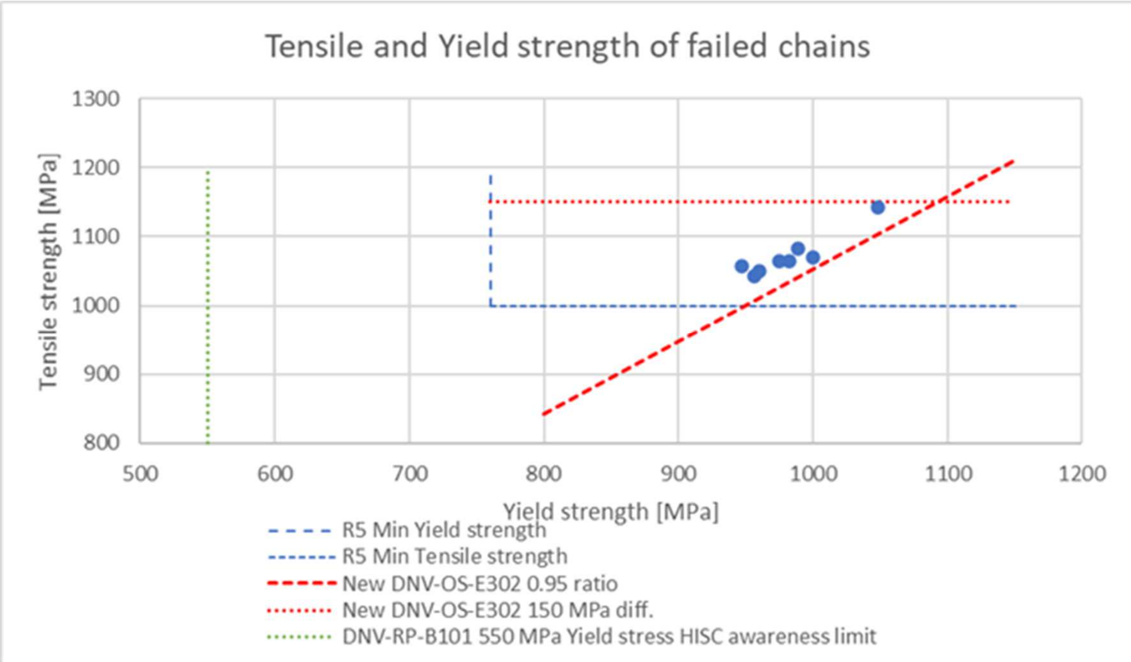


Figure 7-3 Failed chains mechanical properties- eight cases with measured composition on the failure report.

Most failure reports included measurement of material hardness in base material (12 cases), and in the vicinity of the crack initiations, near the surface in straight part failures (4 cases) and near the surface in crown failures (5 cases), which are presented in Figure 7-4. It is noted that the base material hardness is close or just above the recommended limits by ISO21457 (332 HV) and DNV-RP-B401 (350 HV). For reference the minimum tensile strength specified for R5 chains (1000 MPa) corresponds to an expected hardness of 311 HV.

From the failure reports it is most importantly noted an increase in hardness by approximately 50 HV compared to bulk material near the surface in crown area in the vicinity of crack initiations, and very high increase in the straight part (up to 600 HV), which is related to observed respectively local deformed and untempered martensite, section 7.2.1 and 7.2.2.

The reduction of area and elongation at failure from tensile tests performed in base material on eight failure reports is presented in Figure 7-5. The limits defined by DNV-OS-E302 for R5 chains are also presented. All chains comply with the specification.

Eight failed links were tested for impact energy per Charpy test at -20°C, as presented in Figure 7-6. Test samples were taken at different parts of the link as presented: base material (straight part opposite the weld), crown (or bend) and straight part on the side of the weld.

Only one failed link does not comply with the average energy limit defined per DNV-OS-E302 Table 3.

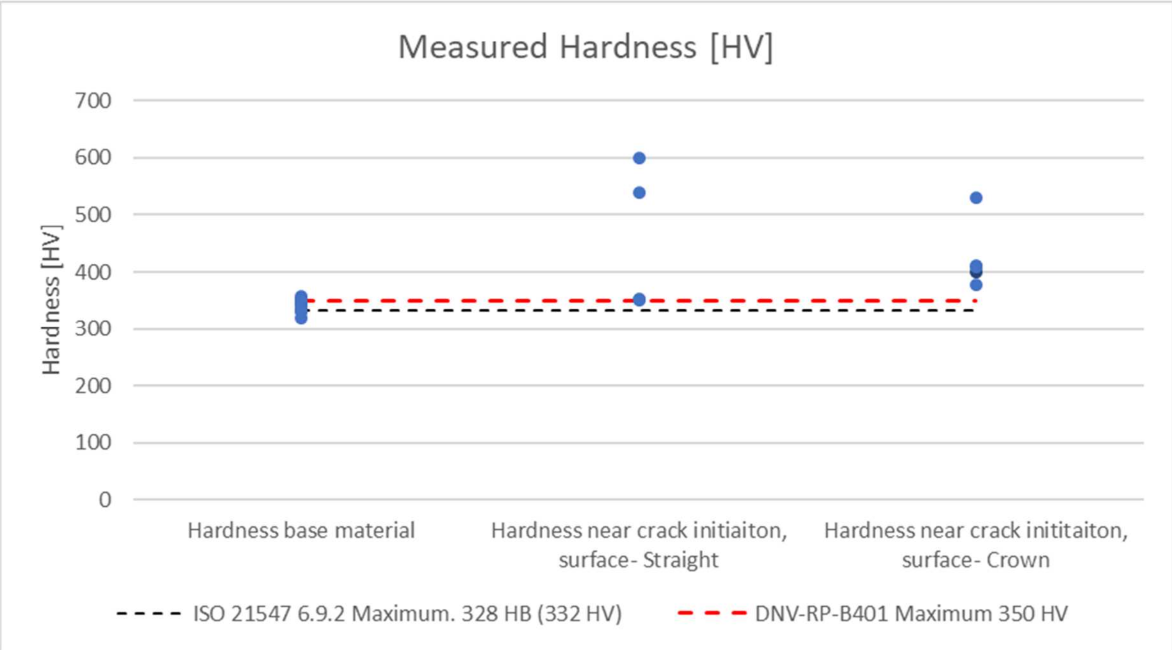


Figure 7-4 Hardness measured available from the failure reports.

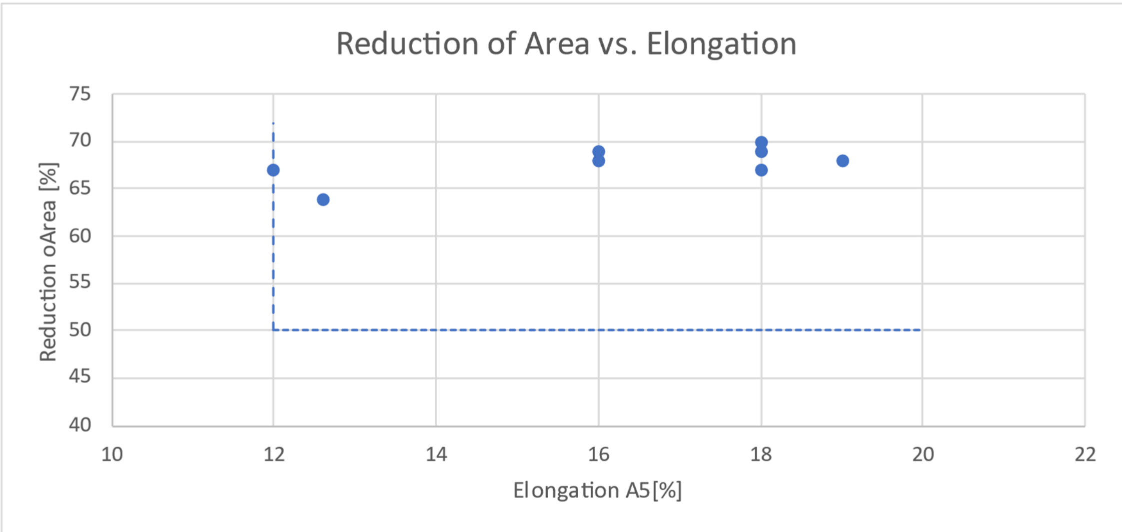


Figure 7-5 Reduction of area and elongation at failure measured in failure reports. Included DNV-OS-E302 R5 limits.

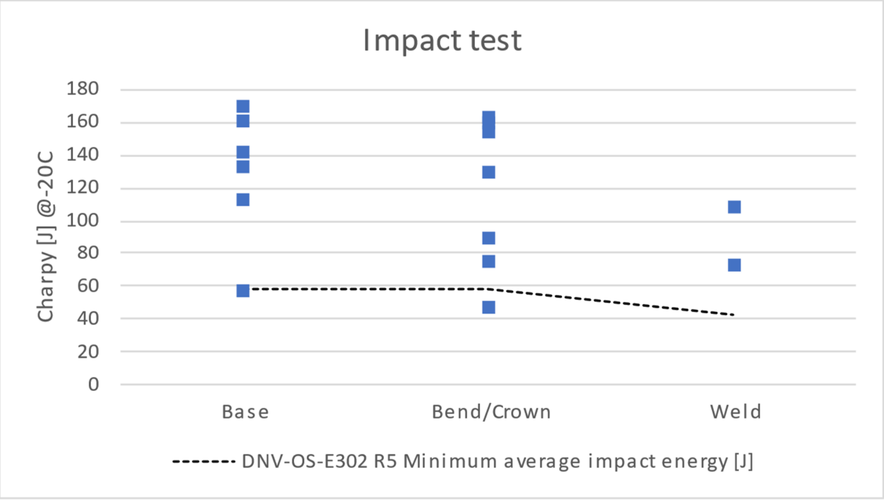


Figure 7-6 Impact test results of failed links.

Seven failed links were tested for composition contents as presented in Figure 7-7 and Figure 7-8. All links comply with the composition limitations for:

- Mo, minimum 0.20% per DNV-OS-E302 Ch.2 Sec. 1 [1.3.1] for R5;

- Al, minimum 0.020% per DNV-OS-E302 Ch.2 Sec. 1 [1.2.2].

In the figures it is also shown the composition for a chain manufactured in 2008 and still in service without failures. It is noted a different composition compared to those reported in the failure reports. This parameter shall be further investigated in the proposed test program.

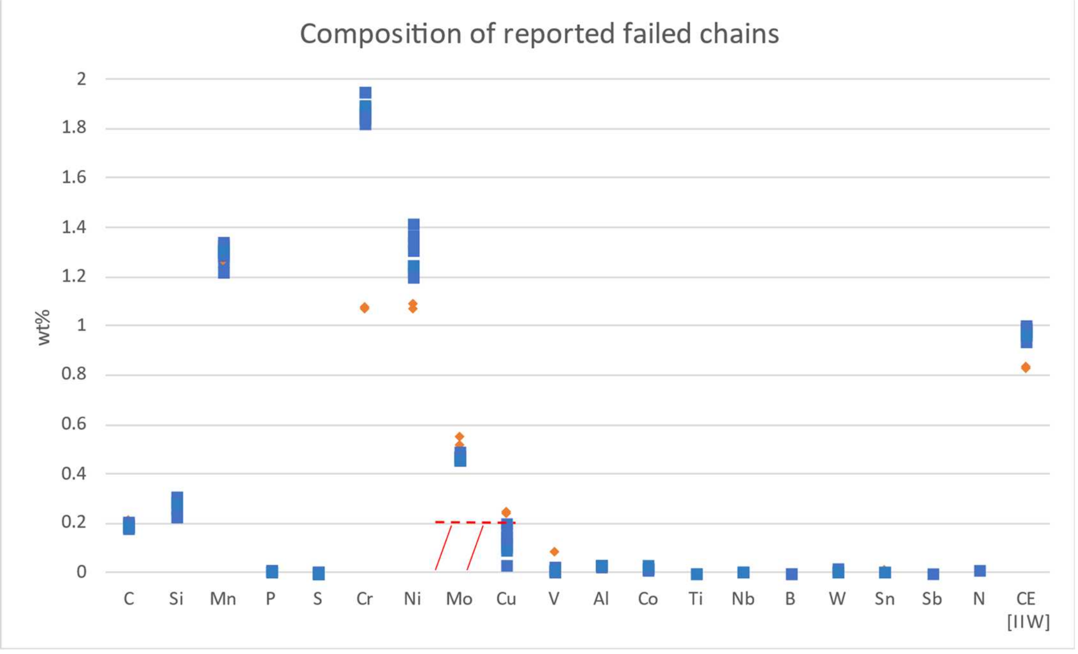


Figure 7-7 Composition of failed links, blue squares- 7 reports available. Orange diamonds correspond to a chain manufactured in 2008 and still in service without reported failures. Note Mo minimum content specified per DNV-OS-E302.

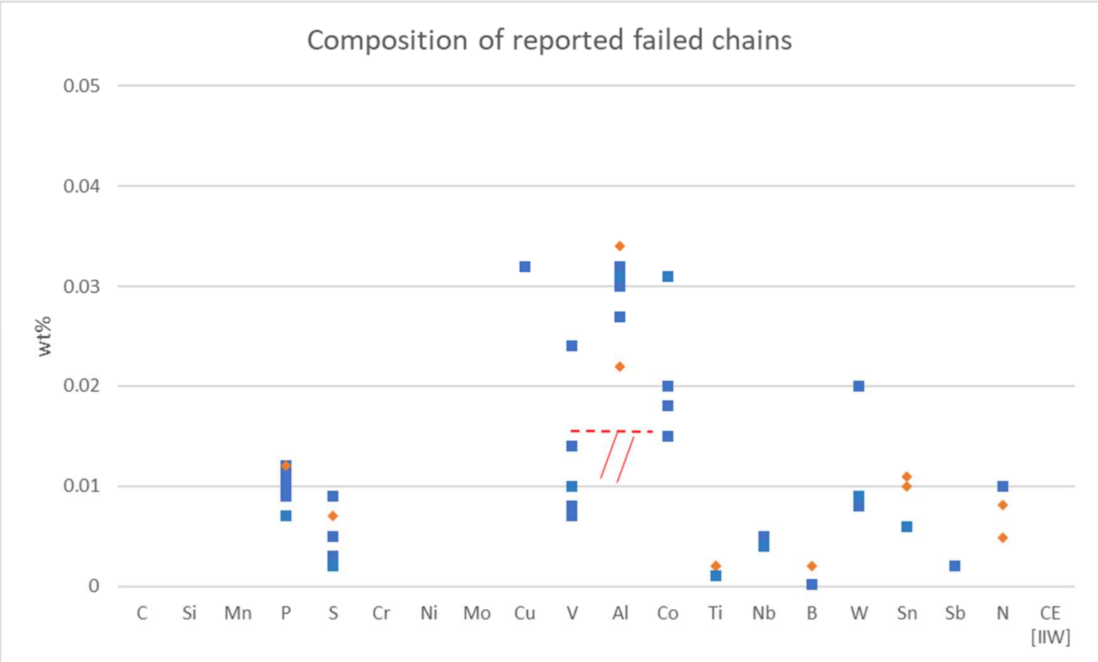


Figure 7-8 Detail of composition of failed links. Orange diamonds correspond to a chain manufactured in 2008 and still in service without reported failures. Note Al minimum specified content per DNV-OS-E302.

7.2 Crack initiation details

Following it is presented a summary of the significant observations extracted from the failure reports considered.

It has been found adequate to differentiate between the two main crack initiation areas: crown and straight part of the links, because of the different specific conditions.

7.2.1 Straight area fractures- crack initiation

Cracks in the straight area of the links most commonly initiate at a 1-2 o'clock position, see Figure 7-9. These initiation locations coincide with contact or drag wear marks as shown in Figure 7-10. It is noted that this location doesn't correspond to a significant stress concentration for chain tensile loading, but some proof load tensile residual stresses are present, see section 2.4.3.

The location of the drag and contact marks are consistent with handling of the chains in yards by dragging over rough surfaces at significant speeds or side to side chaffing and pulling over the stern roller under high load, causing local heating leading to phase changes.

In general, the material microstructure is of quenched and tempered material with a microstructure consisting primarily of tempered martensite, as expected for the mooring chain material. The exception is that it has been observed thin surface layers of untempered martensite (Figure 7-11) in the vicinity of the crack initiation and associated to the contact or drag wear marks. Not all the reports observed this layer of untempered martensite which can be attributed to corrosion having removed it before chain retrieval. High hardness values were also measured near these surface areas with up to 600 HV, while the base material has approximately 330 HV (which corresponds well with the measured tensile strength).

This type of surface microstructure and hardness was not observed in sections outside the areas with dents or wear marks.

The high hardness of the material indicates that local microstructural changes have occurred, supporting the hypothesis of the wear marks creating a local heating effect. The hardened material is known to be more susceptible to hydrogen embrittlement.

It is highlighted that untempered martensite is a hard and brittle material which might be sensitive to HISC or hydrogen embrittlement as per /5/, /16/, /24/ and /25/, and supported by the slanted cracks have been found such as depicted in Figure 7-12. The slanted cracking is observed for other deformed microstructures and could possibly be further promoted by hydrogen. High material hardness increases the probability of cracking at lower strains than that for the bulk material.

Such observations allow to conclude that crack initiation in straight area of the links result from the presence of untempered martensite or highly hardened material caused by high contact loads or drag wear.

Figure 7-9 Example of straight part crack. Initiation at 1-2 o'clock position and single brittle crack surface

Figure 7-10 Example of contact and drag marks location.

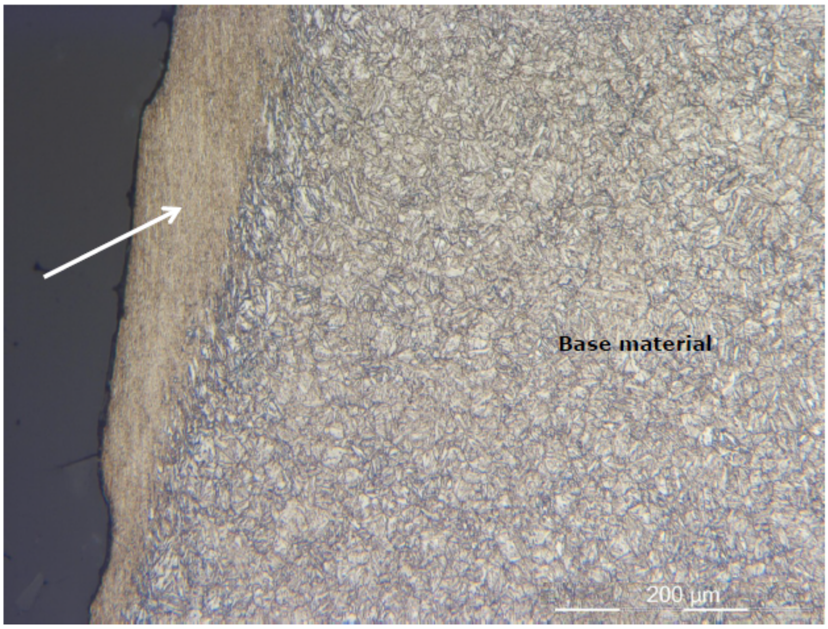


Figure 7-11 Example of untempered martensite layer observed in the vicinity of a crack initiation on the straight part of the link.

Figure 7-12 Example of slanted micro cracks observed in the untempered martensite layer. This type of surface microstructure was not observed in sections take outside the areas with dents or wear marks.

7.2.2 Crown area fractures- crack initiation

Cracks in the crown area of the links most commonly initiate at the intrados of the section, see Figure 7-13. These initiation locations coincide with high interlink contact dents or wear marks as shown in Figure 7-14. It is noted that this location doesn't correspond to a significant stress concentration for chain tensile loading, but high proof load tensile residual stresses are present, see section 2.4.3.

The shape of the contact marks are consistent with handling of the chains and pulling over the stern roller under high load, causing local severe wear.

In general, the observed microstructure was typical for a quenched and tempered material with a microstructure consisting primarily of tempered martensite, as expected for the mooring chain material. But local surface macro and microscopic structure deformations are noted associate to the referred dents. Significant elevated hardness values were also measured near these surface areas with up to 400 HV, while the base material has approximately 340-350 HV.

The high hardness of the material indicates that local microstructural changes have occurred, supporting the hypothesis of the interlink wear marks created a local deformed microstructure. The hardened material is known to be more susceptible to hydrogen embrittlement, as per /5/, /16/, /24/ and /25/.

Such observations allow to conclude that crack initiation in crown area of the links result from the presence of hardened and deformed martensite caused by high interlink contact loads and wear.

In terms of time frame for the crack growth, there was one well documented case where a portion of seabed chain (120-150t load) failed at 200t tension 3 months after surviving a tension of 300t. The said chain links were exposed to CP due to a laying chaser wire. In the same chain but in a position near the handling vessel but far from the rig CP, another link presented a crack surface with multiple brittle and fatigue phases.

Figure 7-13 Typical location of a crown crack and initiation area

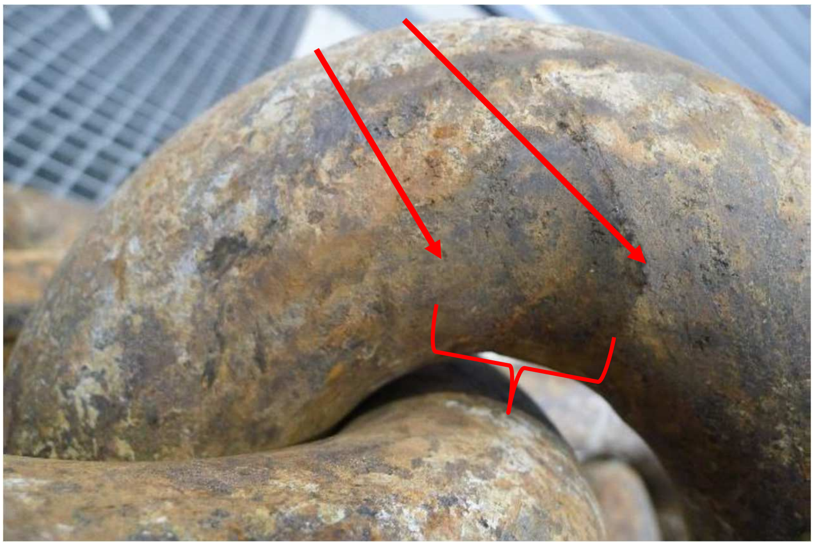


Figure 7-14 High contact/wear marks in the crown area

7.2.3 Crack growth

Most fracture surfaces show a single brittle fracture, see Figure 7-15. In one of the failure cases the fracture surface shows a clear sequence of fast and crack arrest areas indicating that the failure was progressive upon a sequence of high load events ("fast") and lower fatigue dominated phases ("slow"), Figure 7-16. Two other crown failures show a similar but not so clear crack surface.

Microscopic inspection of the fracture surfaces showed mostly a fracture mode with intergranular cracking (see Figure 7-17) and to lower extent transgranular cleavage crack propagation. The observed brittle fracture modes are typical for hydrogen induced stress cracking in ductile materials such as these cases. It is noted that according to recent Sintef findings, there is a possibility that in high strength materials, fatigue crack surfaces may also present an intergranular cracking surface.

Secondary cracking was also observed in most reports (Figure 7-18) further supporting the theory that the crack growth is HISC driven.

Figure 7-15 Most common type of crack surface with single brittle growth and final shear lip.

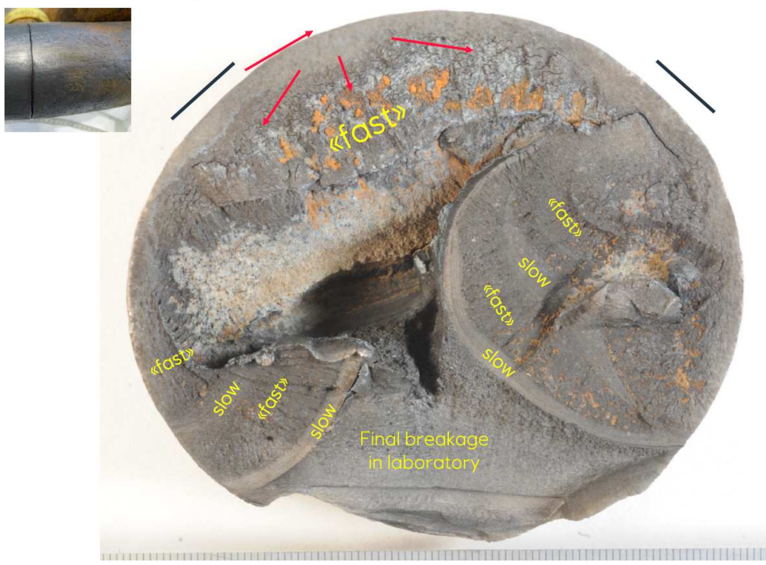


Figure 7-16 Example of breakage surface showing several events of fast/brittle fracture and slow/fatigue growth periods.

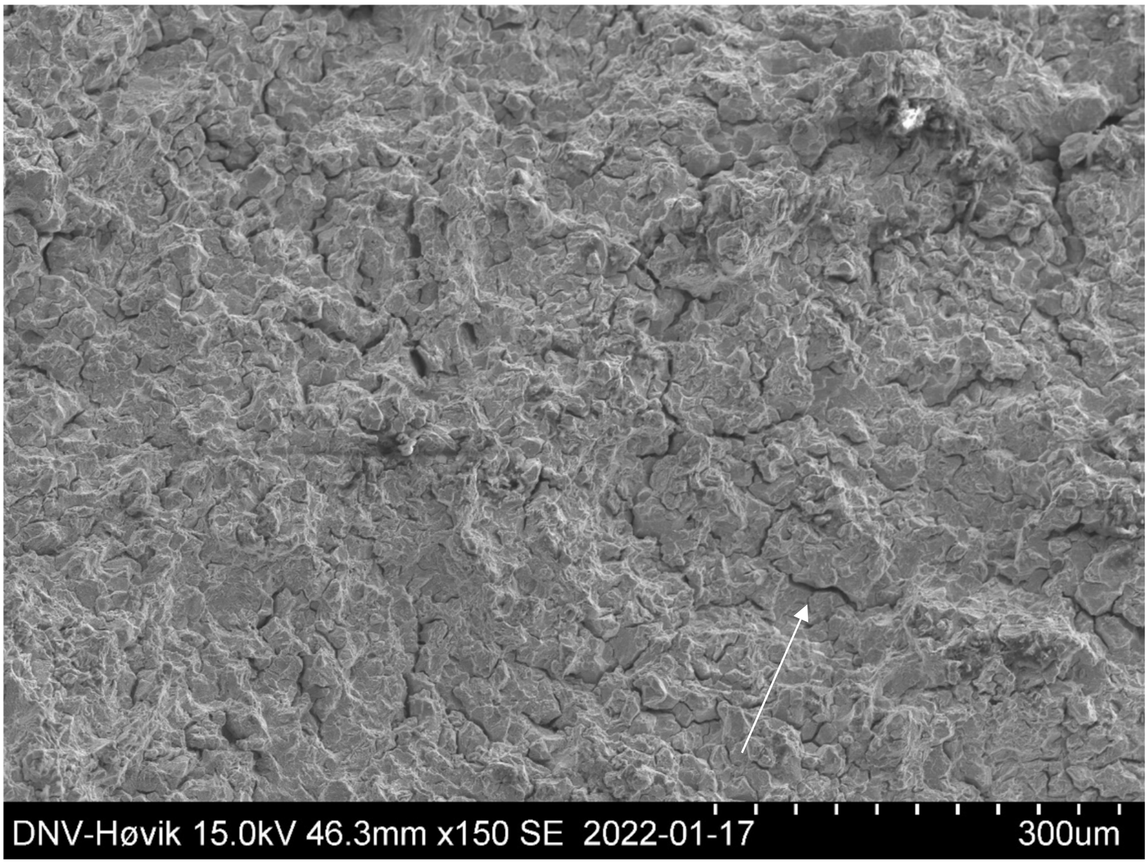


Figure 7-17 SEM image of fracture surface showing intergranular cracking- as per the surface topology corresponding to the grain boundaries. Secondary cracking is also observed- example pointed by white arrow.

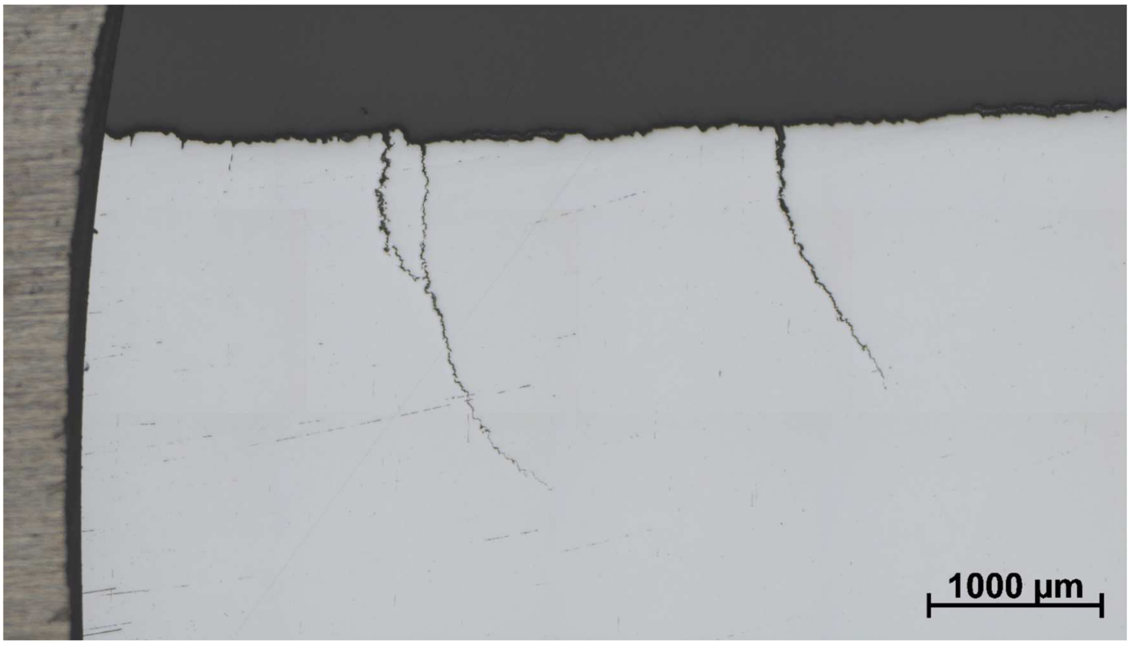


Figure 7-18 Secondary cracking observed along the main fracture surface.

7.3 Lower grade chains susceptibility

The historical setting of the recorded failures in high-strength chains is defined in the following events:

Reference condition in mobile mooring systems was the use of R4 chains always installed in the rigs and pretensioned on location with help from AHTS and the rig winch systems.

Early 2000's– AHTS start to have ICCP.

2008- First R5 chains certified by DNV

2009- Increase in anchor setting loads

2012- Advent of pre-laid mooring systems using R5 chains and rapid decrease of R4 chains in service

2016- First confirmed R5 chain failure attributable to the mechanisms discussed in this report.

This historical sequence hinders the use of historical failure data to conclude on the R4 or R4S chains susceptibility to hydrogen as factor for failure since the loading and ICCP has changed. Nevertheless, it is noted that:

- Higher strength materials are known to have higher hydrogen susceptibility as expressed in ISO, NORSOK and DNV standards, see section 6.2.

The HISC sensitivity typically increases as the strength of the material increases. It is not fully clear if this is related to microstructure or general stress level that can be achieved in the material (or other reasons). However, based on this it is likely that R5 could display lower HISC resistance than R4. Whether this applies both the surface hardened layer and the bulk should be better clarified.

- Higher strength materials have higher base material hardness which can result in sensitive high hardness layer of surface layers affected by external events such as wear and heating.

The quantification of those factors shall be part of further evaluations, see section 9.

7.4 Summary of observations

A simple summary of failure conditions and observations is presented in Figure 7-19.

There are two different locations of the identified fractures:

- Straight part, initiating from outer areas of the section. Occurring both on welded and non-weld side. These coincide with drag wear marks with very high measured hardness and some cases of observed untempered martensite.
- Crown (or bend) part, initiating from the inner area of the section. These coincide with interlink high contact stress areas from proof load and chain handling high loads, and wear. Crack initiation in area with observed increase in hardness close to the surface compared with bulk hardness. In one failure case significant plastic deformations were observed due to adhesive wear causing untempered martensite.

All chains have been subject to different levels of cathodic protection due to anchor handling operations by vessels with ICCP and mooring of rigs with SACP. Microscopic fracture examination showed intergranular crack growth which in ductile material could be indicative of HISC driven cracking.

The chain material complies with the specifications with exception to:

- Hardness on locations subject to wear and contact stress conditions.

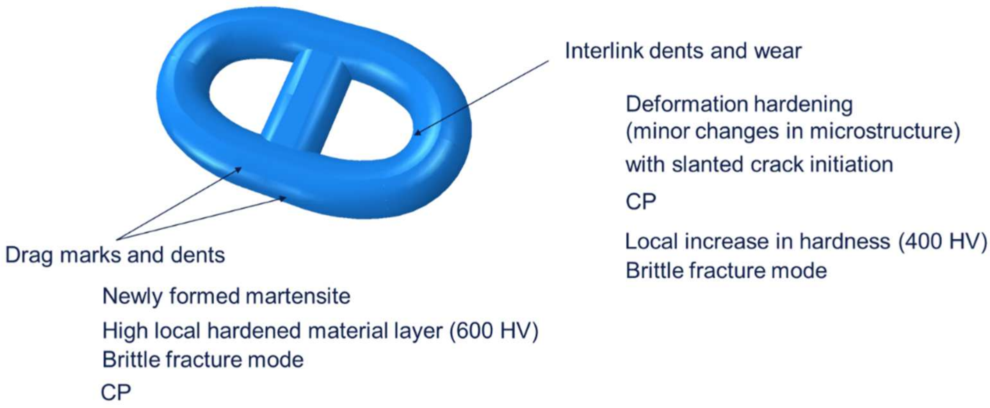


Figure 7-19 Summary of main crack characteristics.

8 RESEARCH PERFORMED

Several research initiatives have been undertaken by different industry players, and in this section are presented the most relevant for the understanding of the failures root causes

8.1 Weld corrosion

Following that some chains were found with visible corrosion grooves in the weld line area, section 8.4.2, DNV performed detail chemical analysis on several points near and through the weld. Measurements revealed a slightly lower content of alloying elements (silicon, chromium, manganese, nickel and molybdenum) in the weld compared to the bulk material. The difference is small but could still cause local galvanic corrosion. Other root causes have also been indicated by other studies.

All material combination variations were still within the limits specified.

8.2 Hydrogen embrittlement susceptibility- Vicinay

SSRT testing contributes to a general observation of the sensitivity of a material to degradation due to influence of hydrogen. There is currently no basis to directly conclude if a material has an adequate performance solely based on SSRT.

Constant tension tests are aimed at estimating the limit in terms of fracture toughness for when a crack may propagate under constant loading. The test could be useful for establishing this limit, however, there are some uncertainties associated with the influence of the initial defect geometry and the pre-loading loading.

The following data has been presented by Vicinay in Tekna Seminar February 2019, regarding SSRT (Slow Stress Rate Testing) with CP and Constant Tension Testing of different chain material grades: R4, R5 and R6, as presented in Figure 8-1 to Figure 8-2.

Testing equipment limitations restricted the completion of some test runs marked with the minimum value obtained in Figure 8-2.

The main conclusions which are possible to draw:

- R4 and R5 don't differ much in terms of the test results for the materials tested.
- All grades are sensitive to CP and show a significant reduction of ductility under -850mV and -1200mV SSRT tests, compared with air and synthetic water tests, Figure 8-1.
- Materials with increasing strength could experience a significant reduction in the crack propagation resistance under the influence of hydrogen, Figure 8-2. For higher strength these values start to be so low that they may explain why short cracks can propagate in the chains bulk material under the expectable residual stresses and those arising from anchor handling and operational loading.

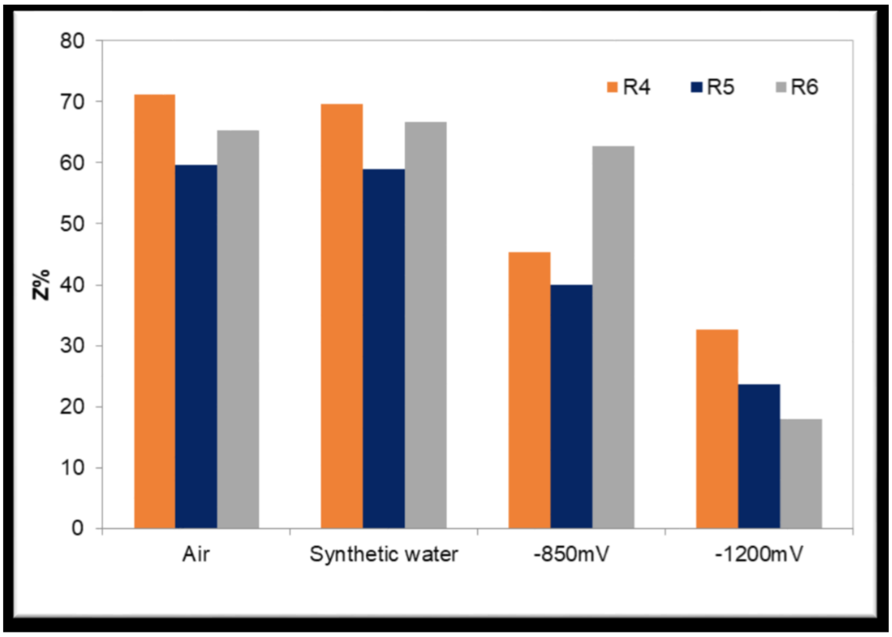


Figure 8-1 Vicinay SSRT testing data summary. Per ASTM G129. Z- Area reduction rate.

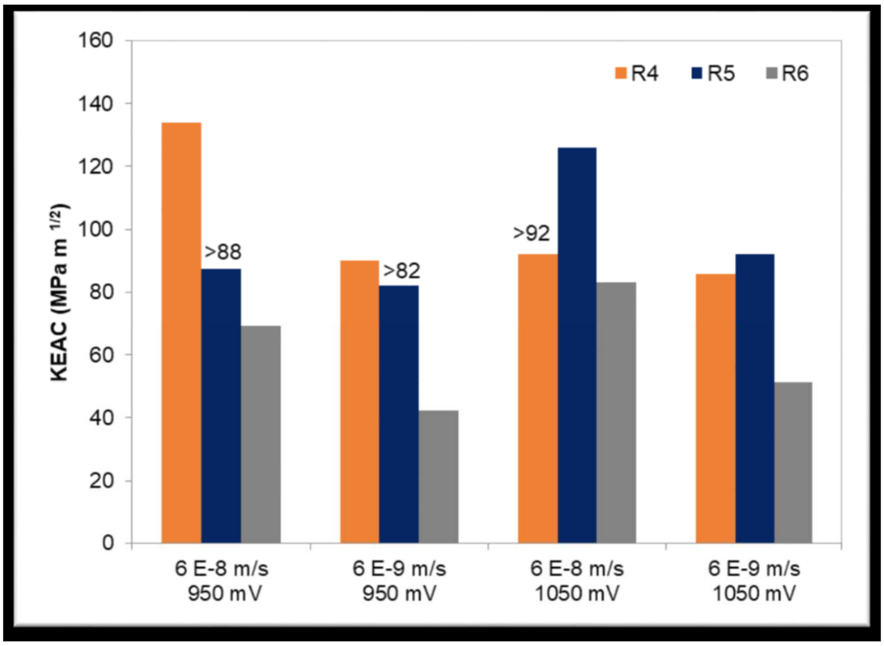


Figure 8-2 Vicinay Constant Tension test results for R4, R5 and R6 material grades. Per EN ISO 7539. KIEAC-Environment assisted cracking stress intensity.

8.3 Hydrogen embrittlement susceptibility- DNV

Slow strain rate testing (SSRT) of four smooth specimens have been conducted in tap water containing 3.5wt% NaCl (for now on denoted seawater), under Cathodic Protection (CP). The two chain material classes R4 and R5 per DNV-CP-0237 have been tested at a strain rate 1.0x10-6 [s^{-1}], CP of -1050mV Ag/AgCl at 4.5 ºC, to document the material grades susceptibility to hydrogen induced stress cracking. In addition, one air tensile test results of the same R5 material was tested in air prior to the environmental testing, and is shown for reference.

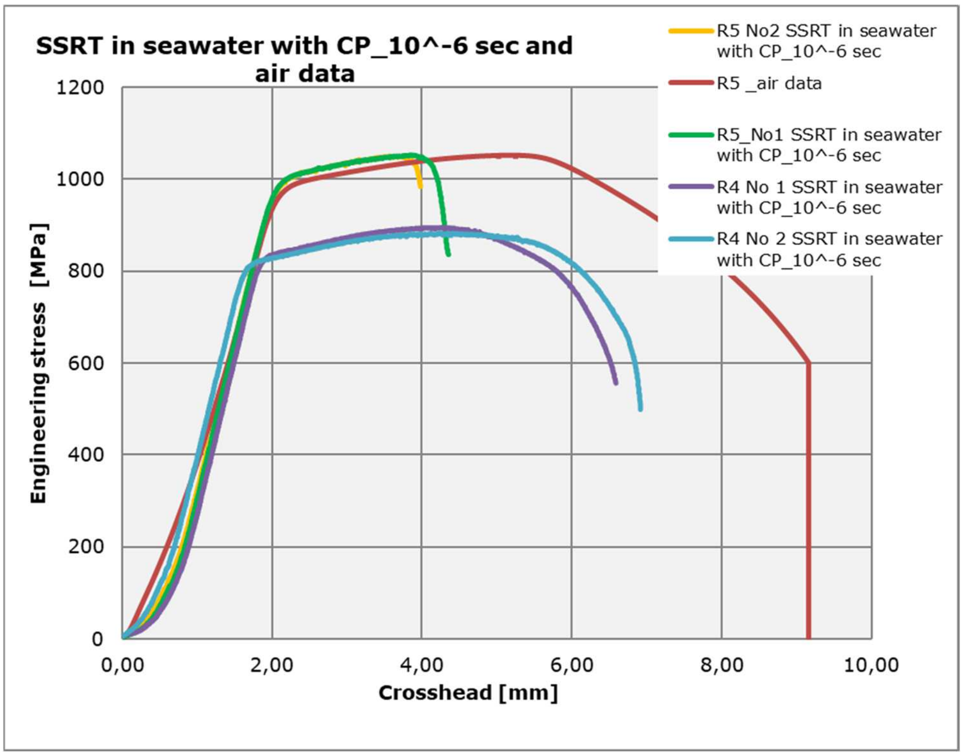


Figure 8-3 Results from SSRT. Crosshead refers to deformation measured in the test machine structure.

Crosshead refers to deformation measured in the test machine structure and therefore include some effect of the machine stiffness and more notoriously the machine clamps effectiveness as observed in some deformation at low loads. For the objective of the testing these parameters have no influence, considering that the same machine and sample size was used in all tests and only relative comparison is envisaged.

The results show a significant reduction of resilience (reduction of energy absorbed before failure) expressed by the lower extension at failure, for the R5 material tested in seawater with CP.

The same effect but at a lower level is expected from the R4 material as deformation at failure of the samples tested with CP in seawater is higher than that for R5- possibly pointing to less degradation due to hydrogen.

8.4 Failure follow-up inspection program

One of the chain rental companies which suffered a failure performed an extended renewal survey including magnetic particle testing of the weld of 100% of 62 000 chain links.

The chain was a R5 Ø84mm studded chain manufactured in 2014. The failure occurred in 2020.

During the inspections, three main types of observations have been noted:

- Weld defects
- Corrosion in the weld
- Cracks in the stud imprint

Investigations relative to these observations are described in further detail in the following chapters.

8.4.1 Weld defects

Indication in the flash weld have been found after cleaning, visual inspection and MPI of the weld area, see Figure 8-4. These are characterized by being deep compared to the width. Upon discovery, the area with the defect is ground until the defect is no longer detectable, see Figure 8-5. Some of the defects are deeper than the discard criteria of the chain link (7% of the diameter).

From approximately 62 000 links:

- 119 links had indications deeper than 7% of the nominal chain diameter and were discarded
- 778 links had indications shallower than 7% of the nominal chain diameter and could be ground away with an acceptable result

The above means that roughly 1.5 % (~900/62 000) links had transverse indications that were found by MPI and was required to be ground away. Each of these indications have the potential of propagating in fatigue, and it is important that they are addressed.

The source of this defects is understood to be the result of weld lack of fusion.

Changes to inspection procedures after manufacturing are expected to have reduced these events for future production, reference DNV-OS-E302 Ch.2 Sec.2 [2.10].

Figure 8-4 Indication found with MPI

Figure 8-5 Grinding of defect

8.4.2 Corrosion in the weld

Many of the links have a defined circumferential line in or near the weld as shown in Figure 8-6. These lines are of varying depth, and the effect on the chain link performance is unknown. However some of the lines are quite deep as shown in Figure 8-6. A cross section was taken in one of the links, Figure 8-7 and showed a very blunt shape with low potential for stress concentration- showing that corrosion is the dominating mechanism and “sharp” hydrogen dominated hydrogen cracks are not easily nucleated.

One theory for the source of these groves, is that they are generated by galvanic corrosion. This can occur if the material properties in the weld are different from those in the base material. A specific investigation was performed by DNV as presented in section 8.1 and confirmed the existence of the base conditions for this to occur.

Figure 8-6 Corrosion in weld

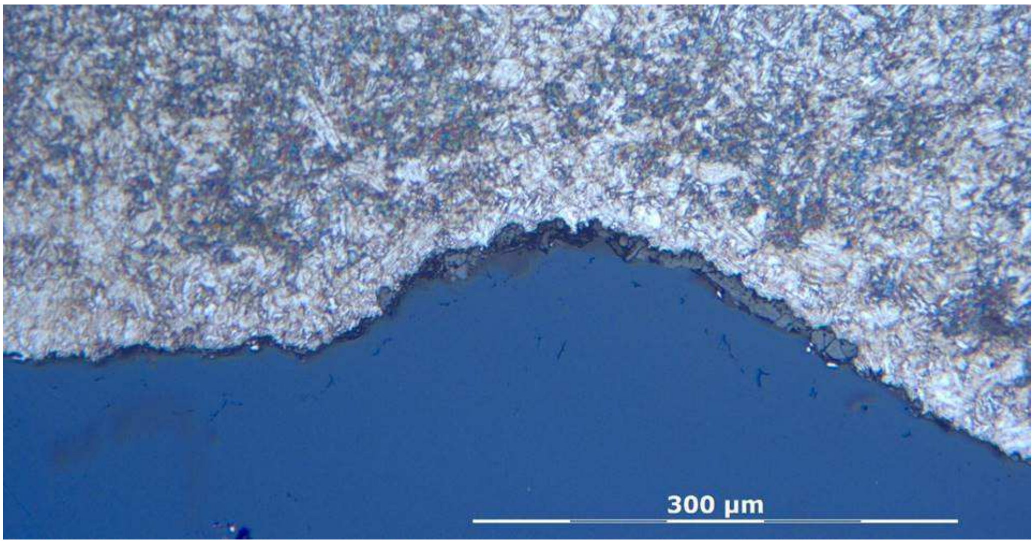


Figure 8-7 Cross section of weld groove.

8.4.3 Cracks in the stud imprint

During investigation of a failed link in the laboratory environment, when removing the stud in one of the links, cracks in the stud imprint were discovered, see Figure 8-8 to Figure 8-10.

Figure 8-8 Crack in stud imprint

Figure 8-9 Crack in stud imprint after cleaning

Figure 8-10 Depth of crack in stud imprint

The cracks shown in Figure 8-8 to Figure 8-11 are in the longitudinal direction, and as such do not affect the ultimate strength of the chain link. The fatigue life impact was studied as presented in section 8.4.3.1 and 8.4.3.2, and all indications point to be negligible.

The root cause of these cracks is unknown, and it might be of interest to study it further.

The cracks may be detected by two methods:

- Cutting the stud and perform visual inspection in the stud imprint
- NDT by Phased Array Ultrasonic Testing specific procedure.

From a total of 2 970 links inspected, findings were made on 688 links, meaning that ~23% of the links have longitudinal cracks under the stud.

All cracks seem to be on the weld side imprint which can be justified by the higher local diameter.

8.4.3.1 Crack surface visual inspections

The main concern relating to this degrading mechanism is if the cracks are growing in a fatigue like manner during cyclic loading. It was therefore decided to open one of the cracks in the chain and investigate the crack surface, see Figure 8-11 and Figure 8-12.

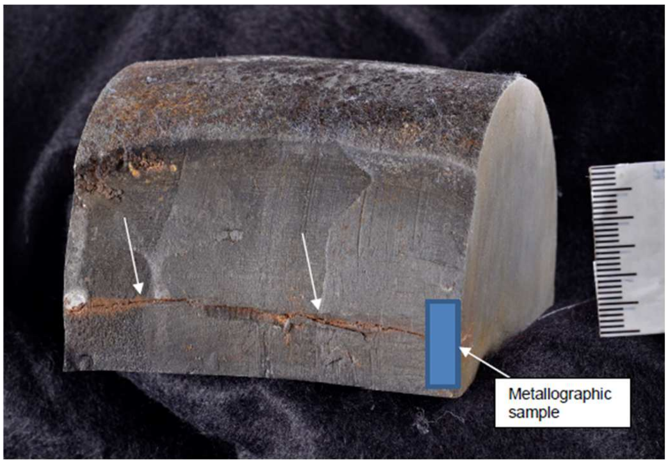


Figure 8-11 Longitudinal crack in the stud imprint

Figure 8-12 Mechanically forced open fracture surface

In addition to the first chain referred to in section 8.4.3, longitudinal cracks were found using MPI on chain links from another chain rental company during inspections. These cracks were located in the inner chain bend and were surface breaking, see Figure 8-13. When removing the stud on the link, a crack was also discovered in the stud imprint, see Figure 8-14. The link with cracks was subject to investigation of the fracture surface.

Both the investigations of both chain links concluded that the fracture surfaces do not have visual signs of fatigue crack growth.

Figure 8-13 Longitudinal crack in the chain bend (DSM chain)

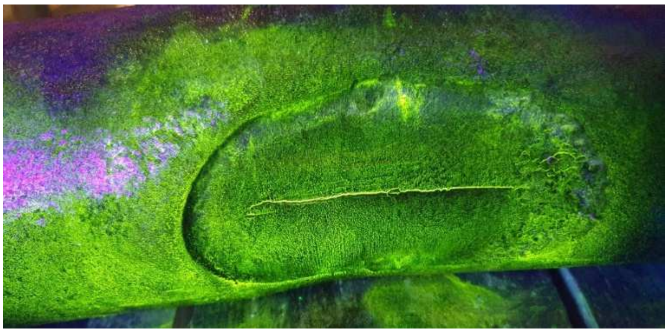


Figure 8-14 Longitudinal crack in stud imprint (DSM chain)

8.4.3.2 Fatigue life of links with longitudinal cracks

One chain segment of 8 links on which 6 links had longitudinal cracks measured by PA NDT, was subject to tension-tension fatigue testing.

The longitudinal cracks length did not change during testing and the fatigue failure originated in a typical hot spot location with an expectable fatigue life.

8.5 Double chain failure follow-up

Following a double failure occurring in a single mooring line one operator and the rig owner performed an extended investigation of the failure including:

- Detailed chain utilisation history identification
- Tensile-tensile fatigue testing of chain segment
- Failure investigation including material testing in the perspective of fracture mechanics characterisation.

8.5.1 Chain failures evaluation

In this case the following failure types were found:

- Crown fracture. The cracks were observed to have started from the 9 o'clock position of the crown in contrast to the local highest stress area which is located outside area of the crown (12 o'clock). The cracks were found to be associated with interlink high contract stress areas and plastic deformation, correlatable to the geometry and stress condition of the chains while running over the stern roller or winch drum with plastic deformation in repeated high loads.
- Straight side fracture. The cracks were observed to have started from the outside surface of the link. During the survey several cracks were found. These were ranging from a few millimetres deep, covering wear zones only, to 3/4 around the circumference, crossing one or two wear zones. Smaller cracks were blunt, while larger cracks had strong indications for being active until recently. The wear marks are consistent with the contact of the chains with the yard ground, stern roller and generally rough handling. In some places in the wear zones increased hardness was observed. The hard surface layer was identified as untempered martensite most likely formed due to friction wear.
- It is assumed that untempered martensite will start cracking by either load or CP. Neither needing to be very high. High load and CP level is believed to be of importance for the growth further into the base material. Limits for loads and CP of the initial cracking should be investigated.
- Some observations of failed link fracture surfaces show a mix of brittle intergranular (fast) fracture mode and fatigue crack progress in a highly loaded link, while other shows a single (slow) brittle failure in a low loaded link.
- In the fast crack growth cases, it was possible to correlate to hydrogen embrittlement caused by hydrogen from cathodic protection and high loading:
    - During anchor holding power testing
    - During pulling of anchors
- In the slow crack growth case it was possible to correlate the CP current source to a nearby connected zinc coated chase wire.

These observations enriched by deep operational knowledge of the failed chain, made by a third party concur with those made by DNV from other failure reports, section 7.1.

8.5.2 Fatigue testing of chain with plastic deformation in crown

A chain segment was tested for tension-tension fatigue in seawater and fatigue life was according to DNV-OS-E301.

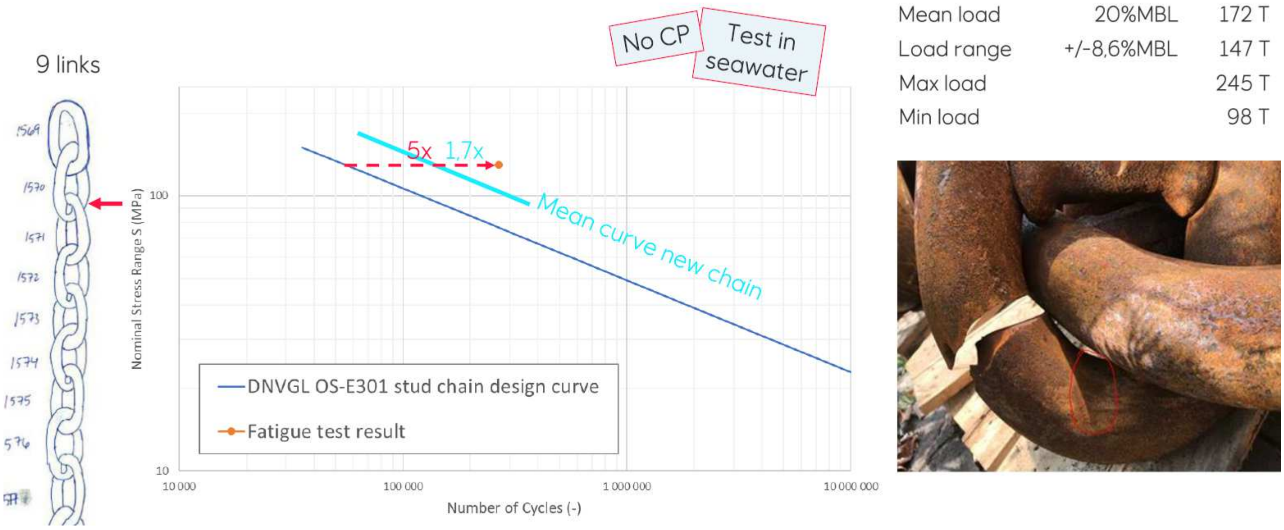


Figure 8-15 Fatigue testing results of chain with crown plastic deformation

8.5.3 Crack growth rate

For the same project a comparative material testing including crack growth rate was performed. Samples of R5 chain were taken from the same chain which had experienced a failure, and compared with R4 chain material, with the following results:

- Crack growth rate in the tested R5 material is approximately 2-3 times higher than in R4 both for CP and free corrosion
- Crack growth rate with CP is about 10 higher at 0.5 Hz than at 10 Hz testing, indicating the importance of the environment exposure conditions.
- Effect of CP versus free corrosion in the crack growth rate is the similar for R4 and R5

Tests with CP were performed at -1050mV.

It is considered that a difference of 2-3 times in CGR is not sufficient to justify a significantly different of failure rate between the different material grade chains. A combination of changes to operational factors such as load levels and CP exposure might need to be considered. Testing should be continued to clarify these uncertainties.

8.6 Chain rental inspection

A chain rental company has presented a summary of its inspection activities performed after suffering four failures on its inventory of Kenter links, swivels and mobile mooring chains- in R4 and R5 material grades.

The survey was performed over 3 years and more than 30 000 m of R5 chain were inspected:

- Suspected manufacturer: Visual+measurements+20% MT+100% MT on welds.
- Other manufacturer: Visual+measurements+5% MT (20% for chain over fairlead
- Findings:
  - 2-3 marks in crown area per segment which were grinded and MT checked
  - Some recesses in the weld which were grinded an MT checked
  - 1 link discarded due to cracks on the weld.

The same company inspected more than 400 m of chain tails, chaser-stopper segments and adaptors on which it was found:

- Small cracks and one deep crack on one link in the weld area
- 2 links were discarded upon the visual and MT inspection.

Preponderance of defects is related to weld defects which are expected to be avoided in the future due to changes to manufacturing inspection. Further investigation of weld corrosion effect is included in the proposed test plan.

8.7 Anchor handling overloads

Chain load analysis performed by Delmar in SIMO (Multibody simulation software) and RIFLEX (Riser analysis software) of a typical AHV during a anchor retrieval operation:

- WD= [100m, 300m], water depth
- H_S= [1,5m, 2m, 2.5m, 3m, 3.5m]
- Pay-out= [1.WD, 1.5WD, 1.7WD]
- BP (Bollard pull)= 200tonnes, Bollard Pull
- Only chain- 84mm R5
- Anchor point fixed, no tension control, no wind and current forces

The results as presented in Figure 8-16 and Figure 8-17, concluded on high potential of the target load or even the chain MBL being exceeded, especially in shallow waters (100m vs. 300m water depth) and low pay-out.

Based on these results, Delmar has tabulated the effect vs. sea state limits for anchor handling operations as presented in Table 8-1, resulting in recommended limit values for retrieval operations specially in soft soil.

The analyses performed considered the anchor point as fixed and no tension control applied on AHV. The analyses were performed in order to demonstrate the high tension experienced by the line segment due to vessel movements and how the tension MPM (Most probable maximum) varies with water depth and weather conditions.

DNV is of the opinion that actual line tension load shall be utilized and closely monitored and logged rather than the current focus on bollard-pull. This to ensure the loading history of chains and components in the line, in the various operational phases are not subject to loads which may introduce damages. In case of overload or high unwanted loads occur, or cannot be avoided, the components in question can be traced and subjected to appropriate inspection scope to verify the continued integrity of the chain/component.

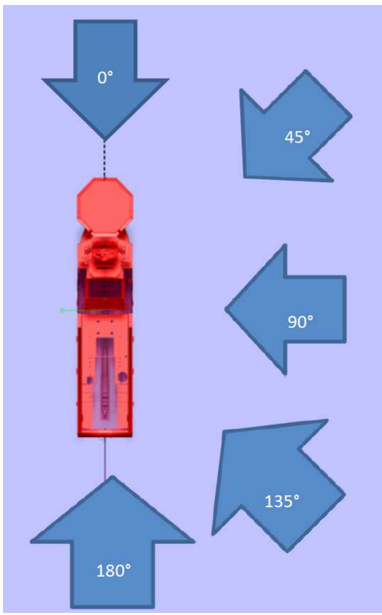
DNV do currently work on a separate initiative to calibrate and differentiate the approach used to achieve pre-tension by the AHV. This initiative aims to ensure loads are not applied with higher values than necessary. The scope of this project is to reduce both the risk of overloading and to reduce the CO2 emissions during the pre-setting and retrieval phases.

Table 8-1 H_S limits proposed by Delmar for retrieval operations. And wave directions considered.

	Hs limits - WD=100m & BP=200t		
Wave direction/ Pay-out	1.3WD	1.5WD	1.7WD
0	1.5	2	3
45	< 1.5	1.5	2.5
90	< 1.5	1.5	2
135	< 1.5	1.5	2
180	< 1.5	1.5	2

	Hs limits - WD=300m & BP=200t		
Wave direction/ Pay-out	1.3WD	1.5WD	1.7WD
0	3.5	3.5	3.5
45	3	3.5	3.5
90	2.5	3.5	3.5
135	2	3.5	3.5
180	2.5	3.5	3.5

The criterias above are based on keeping the 1 hour MPM value less than 0.65MBL



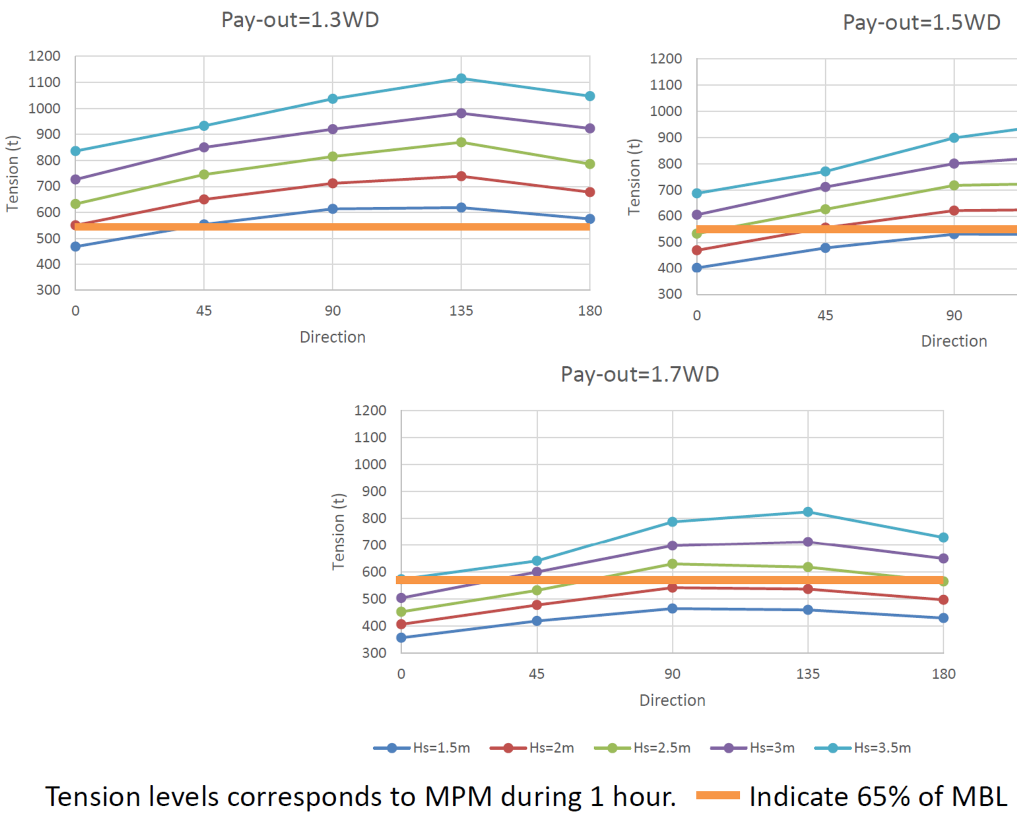


Figure 8-16 Results of Delmar AHV dynamic analysis- 100m water depth

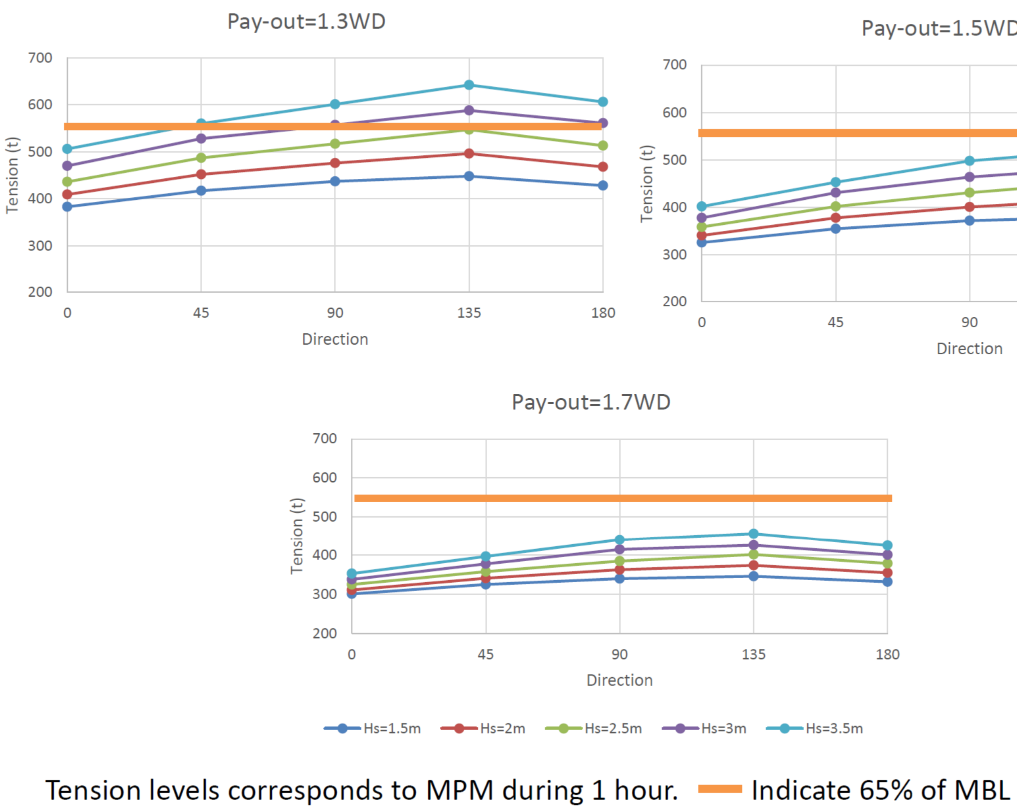


Figure 8-17 Results of Delmar AHV dynamic analysis- 300m water depth

8.8 Research observations conclusions

It is concluded that:

- Cracks in the stud imprint do not represent a threat to the chain integrity if not extending beyond the said imprint area.
- Weld defects are not expected to occur in new chains but inspection procedures should be maintained until statistical data is available to enable changing current requirements.
- Weld line corrosion is not expected to represent a specific threat and specific geometrical acceptability criteria should be revised.
- R5 chains present a reduced fracture toughness compared to R4 material, both in free corrosion and when exposed to CP, per sections 8.2, 8.3 and 8.5.3, but it is not concluded if that difference can justify the failure rates observed.

9 DISCUSSION AND ANALYSIS OF COLLECTED DATA AND OPEN ITEMS ON ROOT CAUSES

In this section Table 9-1 through Table 9-3, it is presented a systematic discussion of the crack initiation and crack growth mechanisms considered to be responsible for the high strength chains failures analysed.

The root causes are divided in 3 vectors, which are discussed for each case:

- Surface condition
- Environment
- Stress conditions

In summary according to previous findings the following is assumed:

- Crack initiation has two slightly different root causes:
    - Straight part- Hardened surface layer from newly formed (untempered) martensite resulting from chain handling operations;
    - Crown- Hardened surface layer from deformed microstructure / untempered martensite resulting from anchor handling operations.
- Crack growth due to hydrogen embrittlement of susceptible material (high strength) exponentiated by load events and CP.
- Hydrogen source: CP (AHV, Rig, Chaser wire), eventually self corrosion
- Stress: Anchor handling loads, Residual stress

The current DNV interpretation of level of knowledge for each item is also presented and research is suggested when no clear scientific data is known to exist. Therefore three levels of further research are assumed:

- 1st level- Confirm base root cause assumptions
- 2nd level- Determine threshold limits for root causes to become critical/significant. Significant to define mitigation actions set limits.
- 3rd level- Study hydrogen role in all the mechanisms. Where assumptions and possible mitigation actions are not dependent

Table 9-1 Crack initiation – Straight part. Root cause

Crack initiation – Straight part			
Root cause	**Parameter**	**Discussion**	**Status/ Gap**
Surface condition: **Hardened surface layer- Straight part of link**	Evidence	Observed initiation points coincide or are near drag marks	Closed
		Some cases with observed untempered martensite layer in vicinity of crack initiation points related to drag marks. Lack of observation in all cases can be attributed to high level of corrosion in the area.	
		Slanted cracks observed in some untempered martensite cases.	
		Local hardness measured up to 600 HV	
	Threshold loading condition for the formation of hardened layer	Pressure/temperature/drag speed combination- Handling	Test- 2nd
		Impact load conditions (such as fairlead, winch and general handling)	Test- 2nd
	Load required for crack initiation and growth in hardened layer	Hardened material (untempered martensite) could be intrinsically brittle and is susceptible to HISC.	-
		Crack might occur during cooling.	Test- 3rd
		Possibility to define crack initiation conditions – load vs. hydrogen	Test- 3rd
	Observation from long term mooring systems	R4 have also been reported to show same type of cracks in drag marks but did not propagate.	Test- 3rd
	Required environmental condition	Role of hydrogen is not obvious. There are other observations of similar cracking (propagation with an angle) in severely hardened surfaces without hydrogen in pipelines.	Test- 3rd
	Time dependency	Not a factor for crack initiation. It is considered mainly a matter of load due to the high hardness.	Closed
	Hardening criticality	Without untempered martensite what would be the risk of crack initiation?	Closed

	It is assumed that a fatigue mechanism should be required and fatigue resistance has been shown to be adequate	
Environment	Salt water with or without CP- discussed above.	-
Stresses	Residual stresses and low to high variable loading stresses- discussed above.	-

Table 9-2 Crack initiation- Crown. Root cause

Crack inititation – Crown			
Root cause	**Parameter**	**Discussion**	**Status**
Surface condition: **Deformation hardening at surface layer- Crown**	Evidence	Observed initiation points coincide with high interlink compression dents/wear marks and deformed microstructure. Dents seem to coincide with stern roller conditions geometry- shock loads and possible stick-slip rotations.	Closed
		Initiation at low loading stress area but with high residual tensile stress (from inside not outside of crown).	1st -Inspect non-failed chains with marks
		Local hardness measured up to 400 HV near the surface. Deformation hardening not easy to detect by metallographic examination. Corrosion may have removed evidence of untempered martensite.	
	Crack initiation mechanism	Highly deformed microstructure due high contact load wear- prone to cracking due to accrued dislocations and oriented microstructure facilitating crack initiation exponentiated by hydrogen source. Possibly related to slanted cracking. Other- It is questioned if untempered martensite is also present.	To be further investigated. Inspection of non-failed cracked chains.
	Threshold condition for formation of deformed structure	Loading conditions in stern roller creating higher local deformation than proof load, may be calculated.	Calculate/Test- 2nd
		Wear conditions can be identified as per OPB static friction threshold.	Calculate/Test- 2nd
		It is questioned why hasn't this condition been identified in lower grade chains: - Increase of anchor setting loads simultaneous with introduction of R5 material grade. - Lower strength implies higher ductility and less hardened material	 Closed Closed

	Load required for crack initiation and growth in deformation hardened layer	Deformed microstructure may ease crack initiation. Highly deformed material is susceptible to HISC.	Test- 3rd Closed
	Required environmental condition	Role of hydrogen is not obvious, however, as the local hardness increase is less than for the surface in the «straight» part it is more likely that hydrogen could play a role in the fracture initiation.	Test- 3rd
	Time dependency	Not a factor for crack initiation. It is mainly a matter of load due to the high hardness. For intermediate hardness levels, hydrogen presence and therefore time can become a factor	Closed
Environment		Salt water with or without CP- discussed above.	-
Stresses		Residual stresses and low to high variable loading stresses- discussed above.	-

Table 9-3 Crack growth mechanism

Crack growth mechanism			
Mechanism	**Parameter**	**Discussion**	**Status**
HISC	Evidence	Observed intergranular and/or transgranular cleavage- Brittle fracture mod. The consistency on which such fracture modes were observed indicate low probability of fatigue being involved. Test plan should anyway be open to fully conclude.	Test- 1st
	Bulk composition and properties influence	Why crack propagates in R5 and not in R4? Historical data is difficult data to interpret.	Test- 1st
		It is known that high strength == higher susceptibility.	
		Crack growth characterisation (fracture mechanics data) to relate with experienced loading and confirm failure possibility by the assumed conditions. Define material specification thresholds and operational limitations.	Test- 1st / 2nd
		Could composition/manufacturing process be changed to reduce sensitivity?	Research– 1st
Slow HISC- low long duration loads [months]	Supporting evidence	Corrosion observed in large brittle fracture surfaces. Large brittle crack surfaces require hydrogen diffusion through the entire volume of the link for which there is not enough service time with CP.	Literature review
		Self corrosion generated hydrogen is considered to be sufficient to maintain crack growth under stresses at the level of residual stresses.	Test- 2nd
		Secondary cracks with inter-granular micro-cracking.	Closed
	Hydrogen source on links away from rig	Entrapment of hydrogen generated in local crack corrosion process (crevice mechanism)	Literature review
		Corrosion from seabed environment (H2S due bacterial activity) might be factor on highly H2 sensitive material	Literature review
	Crack growth process	Hydrogen reduces the material resistance and with residual stresses release promotes inter-granular cracking (brittle fracture mode)	Closed

		Are residual stress and local hydrogen enough for crack growth?	Investigate/Test-1st
	Time dependency	Crack growth rate dependency on load level/CP level/residual stress (uptake and diffusion relation)	Investigate/Test-1st
	Minimum load level for critical crack growth rate	Crack growth rate dependency on load level and useful life and CP level	Investigate/Test-1st
Fast HISC- high short duration loads **[hours]**	Supporting evidence	Single or few brittle fracture surfaces separated by arrest lines with fatigue marks suggest brittle fractures coincide with high load events	Closed
	Hydrogen source	Hydrogen diffusion while links are near rig and AHV- intensive CP	Agree /Confirm w/ measurements
	Crack growth process	Hydrogen embrittlement with very high short loads	Closed
	Time dependency- growth rate	Depending on the hydrogen source level and load level	Literature/Test-1st
	Minimum load level for crack growth	Relation with material toughness and residual stress.	Literature/Test-1st
Fatigue	Is fatigue a factor	No, because: - Material seems to perform as expected after 2 tests performed. - Some failure investigations considering updated sea states and anchor handling loads, concluded that fatigue damage was approximately 1 at failure. (Cases not included in failure statistics)	Closed
	Factors	Local stress raisers (dents, wear marks) Material sensibility- shown not to be a factor by tests performed	Closed

Unknowns	Fatigue at high mean load.	Test-3rd
How to control	Monitor loads from rig and AHV	Closed
How to avoid failures	Include Tension-tension dynamics on system calculations with fibre rope. Keep track of fatigue damage endured due to operational and handling conditions Design for updated load spectrum (Current requirement: only calculation for more than 5 years in location)	Closed

10 INDUSTRY SUGGESTED ACTIONS

Suggestions for rule changes from operators and chain handling companies are presented in this section. All the suggestions are considered to be reflected in the rules changes introduced or to be introduced by DNV- section 11.1, or on the planned and recommend activities- section 11 and 12. The background for each suggestion is also presented.

10.1 Equinor

The following mitigation actions suggestions have been presented by Equinor.

Table 10-1 Equinor action suggestions as expressed in the presentations of Tekna 2022

Subject/Root cause	Proposed actions	Justification
Wear marks and dents	Guideline suggestion on handling of chains onshore: o Chain shall not be pulled over obstacles and sharp objects. o Pulling of chain over ground/deck shall be at slow speed (max 8 km/h). o Quayside surface should preferably be steel plated or soft gravel. o Chain shall not be lifted or handled by sharp or hard objects, such as forklift forks, excavator buckets or similar. Soft slings or special designed tools shall eb used for lifting of chain.	Wear marks and dents have been found to be associated with crack initiations through stress concentrations and hardened material (untempered martensite)
Overloading	Change suggestion on handling of chains offshore. Mooring system and mooring line configuration shall be designed such that the following is met: o Mooring chain shall not be positioned over the stern roller when anchor holding power testing is performed. o Mooring chain shall not be positioned over stern roller during break-out anchors. If low loads for break-out of anchors are experienced, chain may be positioned over stern roller during break-out. o Chain that has experienced high loads over stern roller shall be inspected thoroughly onshore after the operation.	Mooring chain is not designed for high loads when in shark jaws, when being pulled by gypsies or when passing over stern rollers.

Subject/Root cause	Proposed actions	Justification
HISC	Guideline suggestion on cathodic protection: o Vessel Induced Current Cathodic Protection (ICCP) system shall be turned off during operation with chain in the water over the stern roller. ICCP system shall be turned off 6 hours prior to operation. o A fiber rope is recommended to ensure electric discontinuity between mooring chain and work wire when performing anchor holding power test at high loads. A fiber rope is required if ICCP system can not be turned off. o No components with cathodic protection should be left in the mooring system. (Example: Chaser wire (zinc coated) parked on the sea floor). Special consideration to be taken.	Higher grades are susceptible to HISC, and surface damages can lead to fast crack development when chains are exposed to cathodic protection-especially when in combination with high loads.
Condition monitoring	Improve inspection regime	Noted corrosion on initial brittle cracks.

10.2 Delmar

The following mitigation actions suggestions have been presented by Delmar.

Table 10-2 Delmar suggestions as expressed at Ankerhåndteringskonferansen 2021 and Tekna 2022

Subject/Root cause	Proposed actions	Justification
Overloading during retrieval	Recommended limits for Hs during anchor retrieval operations depending on wave direction pay-out, wave direction and WD. Pay-out from 1.3 to 1.7WD. WD =100 m and 300 m.	Delmar analysis (SIMO and RIFLEX) of retrieval operation loading vs wave Hs and direction, and water depth, and payout. Concluded on high potential of ULS being exceeded. Section 8.7.
Hydrogen embrittlement	- Turn off ICCP for all chain handling - Define maximum values for mechanical properties - More active approach to prevent Hydrogen	Observed brittle fracture Failed chain with yield above 1200 MPa (E302 min. is 1000 Mpa)
Inspection	Risk-based inspection interval	Corrosion found in initial crack surface and cracks connected to high loading events while at the stern roller
Grinding	Developing specific grinding procedure for R5	To reduce risk of causing untempered martensite when grinding away deeper cracks and imperfections

10.3 Transocean/Equinor/Intermoor

The following mitigation actions suggestions have been presented by Transocean/ Equinor/ Intermoor.

Table 10-3 Transocean/ Equinor/ Intermoor actions suggestions as expressed at Ankerhåndteringskonferansen November 2019

Subject/Root cause	Proposed actions	Justification
Overloading of anchor chain	- Sacrificial chain over stern roller during high tension - Log tension during anchor handling - Improve guidelines for installation/handling of chain: stern roller, shark jaw, winch drum, chain lifter, handling surfaces, side loads.	Failure investigations show failures resulting from high load events and handling on the stern roller.
Chain handling	- Avoid handling on rough surfaces, to and from storage area - Understand relation between friction, speed temperature and martensite. - Test friction on different surfaces: asphalt, concrete, steel, gravel	Failure investigations show relation between drag marks and crack initiation.
HISC	Limit ICCP during chain handling: - Set acceptable limit on the system - Turn system off during anchor handling - Check of rig ICCP	Failure investigations show hydrogen embrittlement crack surfaces.

10.4 Wintershall Dea Norge

The following mitigation actions suggestions have been presented by Wintershall Dea Norge.

Table 10-4 Wintershall Dea Norge suggestions presented following failure investigations

Subject/Root cause	Proposed actions	Justification
ICCP	Investigate the effect of ICCP/CP on R5 material simulated by various operational scenarios	Failure incidence on R5 chains.
	Evaluate practice to turn off the ICCP system in AHV`s during anchor handling operations	Regulate current industry practice
	Recommend involved parties to monitor and log output from ICCP systems in different operational modus to get a better understanding of the possible effects of such systems.	Failure investigations show hydrogen embrittlement crack surfaces.
Material certification	Identify need for additional technical qualification of R5 chain material	Noted the failed chains are compliant with present regulations
	Consider maximum high hardness values combined with effect of hydrogen for operational procedures	High hardness values measured in crack initiation area

Subject/Root cause	Proposed actions	Justification
Adapter link dimensional criteria	Investigate if the poor fit between the intrados tolerances in a “normal” ø84 stud link and special end link (ø105) introduces any deformation, residual stresses or reduced movement in interlink area as manufactured	Failed adaptor link shape mismatch findings
Storage and handling of mooring chains	Update DNV-OS-302 with regards to establish recommendation for storage and handling of chain.	Observed crack initiation matching chain handling drag marks
Other	The use of safety bulletins/alert following such incidents should be emphasized to the industry to encourage sharing of experiences from incidents between the different suppliers on NCS, operators, drilling contractors, class and authorities	-

It is also questioned:

- Grain size requirement change on E302 2018.
- Composition requirements.
- Requirement to include the end link as part of proof load test E302 2.6.1
- Requirement of hardness test after proof load with adapter link
- Definition of dimensions and tolerances on connection to adapter link
- Defining maximum hardnesss requirements

11 ONGOING AND PLANNED ACTIONS AND INITIATIVES

DNV has implemented and is preparing the implementation of Rule changes intended to eliminate the recurrence of the failures which are the subject of this report. These actions result from own investigations, industry discussions and failure reports observations as presented in the previous sections.

Ongoing and planned activities by other stakeholders are also presented.

11.1 Rules updates by DNV

The following actions have been taken by DNV- marked (Imp), and some are to be implemented in the 2022 rules revision cycle- marked (Ong).

Table 11-1 DNV implemented and ongoing activities

Subject/Root cause	Ongoing (Ong) and Implemented (Imp) actions	Justification
CP	(Imp) Improve offshore handling requirements. DNV-RU-OU-0300:2022 App. D, specific to R5 implements operational measures to prevent hydrogen from CP and reduce HISC risk: - Isolate mooring chain from AHV (Fibre rope insert during anchor handling) - Avoid use of ICCP	Confirmed by testing and failure investigations hydrogen embrittlement and CP is a major factor on reported failures
Material	(Imp) DNV-OS-E302:2022 Added requirement for maximum allowable ratio between yield and tensile strength. Added requirement for maximum allowable ratio between yield and tensile strength.	Observed material with mechanical properties higher than the next grade and too high strength ratios with the resulting low toughness implications
Overloading	Shift focus from “bollard pull” to “actual line load” during AHV operations. (Ong/Imp) Improve offshore handling requirements. DNV-RU-OU-0300:2022 App. D: - installation/pre-tensioning - recovery/breakout - logging of tension data - reduction of impact & overloads - limit use of mooring chain over stern roller above 30% MBL - introduced MBL reduction factors for chains positioned over the stern roller - introduction of inspection procedures if peak loads exceed 65% MBL during anchor handling operations.	Initial FEA shows SCFs when running over stern roller are higher than in straight tension and also occur in different locations Delmar study on sea states overloading, section 8.7.
Weld defects	(Ong) Inspection regime change. DNV-RU-OU-0300: - Grinding prior to MT - VI after each use - Grinding in weld area to remove defects - Grinding procedures to be developed; avoid creating un-tempered martensite (more study/research needed)	Weld defects related failures and defects detected in follow-up surveys
Condition monitoring	(Ong) Use of AHV winch log for fatigue condition updates	Delmar past studies and observations from AH operations, section 8.7.

Subject/Root cause	Ongoing (Ong) and Implemented (Imp) actions	Justification
Transition links	(Imp) DNV-OS-E302:2022 define a maximum adjacent links diameter ratio.	Two of the report failures occurred transition links with excessive diameter ration resulting in inadequate interlink contact.
Un-tempered martensite	(Ong) Improve inspection regime. DNV-RU-OU-0300: - Risk-based inspection interval - Visual, MT and Hardness testing - Require removal of drag marks (Imp) Improve onshore handling and storage requirements. DNV-RU-OU-0300:2022 App. D: - New general requirements - Specific additional requirements for R5 - Focus on loading/offloading - Reduce friction/impact in handling (Imp) Improve offshore handling and storage requirements. DNV-RU-OU-030:20220 App. D: - Reduced acceptability of chain over stern roller while under tension - Reduction of impact & overloads - Reduce friction/impact in handling	Verified the existence of untempered martensite in several failure investigations. It is known that a high hardness surface can be the origin of brittle fractures

11.2 Ongoing activities

The following activities are known to be taking place in different forums in order to define mitigation actions for the failures root causes.

Table 11-2 Ongoing activities for update of regulatory framework

Entities	Subject
GOMO Industry workgroup	Revision of chain handling specification, chapter 11- target completion 2022
DNV	Anchor loads review and compliance criteria. Update of DNV-RP-E301.
Kongsberg Maritime	Logging of loads system development. Improve sampling rates and line load accuracy and make the data easily available both during handling operations and for chain/component history.
DNV	Update of DNV-RU-OU-300 App. D, issued in the July 2022 Edition. (entering into force January 2023) o Onshore handling (including loading/unloading) o Offshore handling/AHV operations (new rules, to be later aligned with revised GOMO Ch.11) o New condition/usage based inspection regime for mooring chain Revision of DNV-OS-E302, Offshore mooring chain, July 2022 + 2023 Edition o Adapter links dimension progression limit o Updated limit to ratio between yield strength to tensile strength and maximum tensile strength

11.3 Planned activities

The following planned activities are known to be in preparation phase for the improvement of the current failure condition.

Table 11-3 Ongoing activities for update of regulatory framework

Entities	Subject
Odfjell Drilling	Odfjell will perform detailed instrumented anchor handling operations on what regards ICCP performance.
DNV	To revise available inspection reports to analyse available data on detected defects occurrence. Develop guidance for setting of anchor loads to reduce the risk of overpulling. Planned for July 2023 Edition of DNV-RU-OU-0300, App. D.

12 RECOMMENDED INITIATIVES

The recommended initiatives are divided in rules changes (assumed to be undertaken by DNV), and a research and test plan.

12.1 Rules changes

Further rule changes in complement to those already being undertaken should result from the ongoing initiatives-section 11 and the testing and research plan presented in section 12.2, namely on:

- Definition of KIEAC and CGR limits for updated high strength chain material grades approval of manufacturers program such as DNV-CP-0237 and of DNV-OS-ES302.
- Update of mooring chain handling criteria and recommendations.
- Update to anchor handling criteria- allowed loads and criteria exceedance consequences.
- Update of fluke anchor setting load definition and operational compliance criteria.
- Update to inspection regime and repair procedures.

12.2 Research and test plan

Considering the discussions and information presented, a research and test plan is proposed in order to clarify the main knowledge gaps identified:

- In terms of fracture mechanics and hydrogen embrittlement susceptibility, what are the differences between the different grades and chain supplies: R4, R5 (failed chains), R5 (non-failed chains), R6.
- Which are the mechanical testing criteria to be used for certification of high strength mooring chains.
- Which are the operational and handling limitations that need to be considered for the safe use of high strength mooring chains.

It is proposed that the main test and research program be performed in a progressive sequence in order to clearly conclude on which failure mechanism is responsible and how to determine material acceptability criteria and operations limitations.

A more detailed scope of the advised research and testing program is presented in Table 12-1. It is also presented which type of main activity is expected to be possible to accomplish each of the objectives:

- Testing. Dedicated test program.
- Analysis. Numerical or analytical analysis such as FEA and fracture mechanics calculations.
- Study. Bibliographical investigation.
- Inspection. Observation and statistical treatment of existing data or materials.
- Instrumenting. Dedicated instrumentation program and inspection of operational installations.

Table 12-1 Complete research and testing program proposed

Item	Subject	Type of activity
1	**Clarification of crack growth mechanism- 1st testing level**	
1.1	Fracture toughness for environment assisted cracking (KIEAC) testing for comparison of the different material grades and supplies.	Testing
1.2	Calibrate obtained KIEAC results with failure cases representative loading profiles. Establish minimum specification values. Characterize crack surface.	Analysis
1.3	Crack growth rate (CGR) testing for comparison of the different material grades and supplies. This testing level shall only be required if the previous KIEAC testing does not justify the failures observed. Characterize crack surface.	Testing
1.4	Calibrate CGR results with failure cases representative loading profiles. Establish minimum specification values.	Analysis
2	**Clarification of untempered and deformed martensite formation- 2nd testing level**	
2.1	Inspection of deformed interlink area in used chains exposed to high loads over stern roller.	Inspection
2.2	Laboratory reproduction of untempered martensite formation. Consideration of contact pressure, contact surface roughness, relative speed, and impact loads. Definition of operational threshold handling limits.	Testing
2.3	Numerical analysis of stern roller loading conditions. Evaluation of plastic deformation and wear levels. To clarify loading limitations during anchor handling operations.	Analysis
3	**Clarification of untempered and deformed martensite as crack initiation- 3rd testing level**	
3.1	Investigate cracking conditions of untempered and deformed martensite. Consider cooling phase, CP levels and stress levels.	Testing
4	**Material knowledge**	
4.1	Impact of chain storage with anodes/ICCP systems	Inspection, Instrumenting
4.2	Significance of applying a maximum hardness specification to avoid HISC. Such as per NORSOK M-001 (328 HB). Also how and where to measure.	Study
4.3	Define design strains or stress criteria for R5/R6 materials as per DNV RP F112.	Study
5	**Handling and operational factors**	
5.1	Fairlead impact on wear and local high contact loading with relation with brittle fractures.	Inspection, Analysis
5.2	ICCP current control performance and impact on chain while exposed to high tensile loads and in curved configuration. Consider results from Odfjell Drilling and Wintershall readings.	Instrumenting
5.3	Effect of high amperage in chain interlink area	Testing
6	**Inspection regime**	
6.1	Evaluate current VI and MPI practise vs. probability of detecting impact/friction damage w/suspected untempered martensite. Analysis of survey campaigns results.	Inspection
7	**Other**	
7.1	Weld line corrosion geometric acceptability criteria	Analysis, Testing
7.2	Manufacturing marks criticality- hydrogen embrittlement and repair criteria upon surveys.	Inspection, Testing

13 PERMANENT MOORING CHAINS

The main contributing factors for the observed failures are currently considered to be:

1. Handling, namely: repeated handling over rough surfaces at high speed (handling yards) or high contact loads (stern roller)

2. Loading- repeated exposure to high tension loads during anchor handling specially with exposure to hydrogen resulting from CP systems.

3. Material susceptibility to hydrogen embrittlement for which the criticality level and supply variability is to be determined.

It is noted that permanent mooring chains can be easily protected from the first two factors if simple operational procedures are implemented.

It is therefore expected that permanently moored installations will not be subject to the same type of failures discussed in this report, if due care is taken during the supply and installation handling of the chains. Conclusion of the research and testing program proposed shall confirm this assumption.

14 FINAL REMARKS

The current data analysis indicates that the most probable leading failure mechanism affecting high strength chains, is hydrogen embrittlement, and that there are two main factors for the failures observed in high strength chains:

1. Operational factors

   Three main operational factors are considered to determine the fractures occurrence:

   a) **Handling** - Formation of a hardened or plastically deformed surface layer. Impact and wear by contact with different types of surfaces and high surface contact loads create hardened surface layers where cracks can easily initiate. Plastic deformation from wear could also initiate surface cracks.

   b) **Loading** – Exposure to high tension loads can facilitate crack initiation in hardened surface layers and expedite crack growth in existing cracks specially in the presence of hydrogen as facilitated by CP systems.

   c) **Hydrogen source** – Hydrogen resulting from CP will facilitate crack growth in susceptible materials, local corrosion may in some cases also contribute to crack growth. The hydrogen embrittlement effect can be exponentiated by application of high tensile loads to the chains.

2. Material factor
   The material susceptibility to hydrogen embrittlement is a major factor. Its criticality depends on the loading levels and amount of exposure to hydrogen. It affects how fast if at all, existing cracks can propagate through the material bulk.

The failure sequence should them be:

- Crack initiation on hardened or deformed surface layer, under CP and eventually high load events.
- Crack propagation in susceptible material, under CP and eventually high load events.

Several rules changes have been implemented and other are being prepared in order to address the failure mechanism factors listed.

A research and testing program is proposed to confirm the failure mechanism identified, determine conditions for the safe use of high strength chains, namely:

- In terms of fracture mechanics and hydrogen embrittlement susceptibility, what are the differences between the different grades and chain supplies: R4, R5 (failed chains), R5 (non failed chains), R6.
- Which are the mechanical testing criteria to be used for certification of high strength mooring chains.
- Which are the operational and handling limitations that need to be considered for the safe use of high strength mooring chains.

Upon completion of the research and testing program presented it is expected that further rules changes can be defined in the following perspectives, enabling safe and efficient use of high strength chains:

- certification of mooring chains

- handling and operational limitations

- inspection regimes.

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/24/ NORSOK Standard M-001:2014, Materials selection

/25/ ISO 21427- Materials selection and corrosion control for oil and gas production systems

/26/ DNV-RP-E301:2021; Design and installation of fluke anchors

About DNV

DNV is the independent expert in risk management and assurance, operating in more than 100 countries. Through its broad experience and deep expertise DNV advances safety and sustainable performance, sets industry benchmarks, and inspires and invents solutions.

Whether assessing a new ship design, optimizing the performance of a wind farm, analyzing sensor data from a gas pipeline or certifying a food company's supply chain, DNV enables its customers and their stakeholders to make critical decisions with confidence.

Driven by its purpose, to safeguard life, property, and the environment, DNV helps tackle the challenges and global transformations facing its customers and the world today and is a trusted voice for many of the world's most successful and forward-thinking companies.