Mooring Chain Fatigue
– New Knowledge with input to both O&G and Floating Wind Systems

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Mooring Integrity User Group meeting, Rotterdam June 16th 2022

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Mooring chain fatigue - new knowledge

- Fatigue testing of new chain
- Assumptions for fatigue design – incorporated in todays standards
- Fatigue testing of used chain
- Corrosion effect to fatigue capacity
- Mean load effect to fatigue capacity
- Fatigue testing of new chain - revisited
- New criteria for mooring chain fatigue design / life extension assessment
- Consequences of new knowledge to O&G assets …
- …. and for Floating Wind!
- Further work

Fatigue testing of new chain

1990´s:
Noble Denton
76mm
R3 / R4

→

Design Codes /
Standards

←

->2019:
TWI
76 & 127mm
R4 / R5

Vendors
Various diam.
R3 - R5

→

Vendor specific
SN curves

Mean load: 20%MBL

Mean load: < 20%MBL

Class society fatigue design

- Based on 20%MBL mean load tests
- Assuming no mean load effect
- Assuming corrosion effect only on diameter, not surface
- Provides an easy method for fatigue damage calculation

- API: TN approach
- DNV: SN approach

- No effect of mean load is associated with high stresses at welds.
- The welds on chain links have no stress increase due to post welding heat treatment.
- The weld is by experience not a regular fatigue hot spot (exception: error in the welds)

- For other components, SN curves are selected based on surface condition
- Corroded surface will not be smooth as new.

Fatigue testing of used chain in Equinor – WHY?

Do we really need to replace all our chains

What IS the fatigue capacity of these chains

How much does interlink wear count?

ARE there any differences between vendors?

What about these pits?

We hardly have any diameter reduction

Start testing !!

Fatigue testing of used chain in Equinor - overview

Test set	Years in operation	"Type"	Condition	2011-2021	2022 ->
A	12	Platform	Wear	4	
B	10	Platform	Pitting	6	
C	9	Platform	Wear	9	
D	4	Platform	Fairlead wear	4	
E	12	Platform	Wear	4	
F	14	Seabed	SRB	4	
G	5	Platform	Pitting	4	
H	16	Platform		3	
I	18	Seabed	Pitting	9	
J	17 / 20	Seabed	SRB	8	
K	12	Platform	Pitting	5	
L	21	Platform	Wear	3	
M	19	Seabed	SRB	7	
N	19	Interm.	General corrosion	4	
O	19	Seabed	SRB	7	
P	19	Seabed	SRB	10	
Q	22	Seabed	SRB + General	4	
R	20	Seabed	SRB	3	
S	16	Seabed	SRB		3

- ~100 full scale tests
- Run to 1st failure
- Mean load set to typical in operation
- Vertical test rig
- Typically 5 links

- Crack search prior to testing
- 3D scanning of surface

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Fatigue testing of used chains in Equinor - Findings

- Mean load has a significant effect
- Surface condition has a significant effect
    - Rough surface from general corrosion
    - Pits from MIC/SRB
- (Limited) interlink wear has no or positive effect (?)

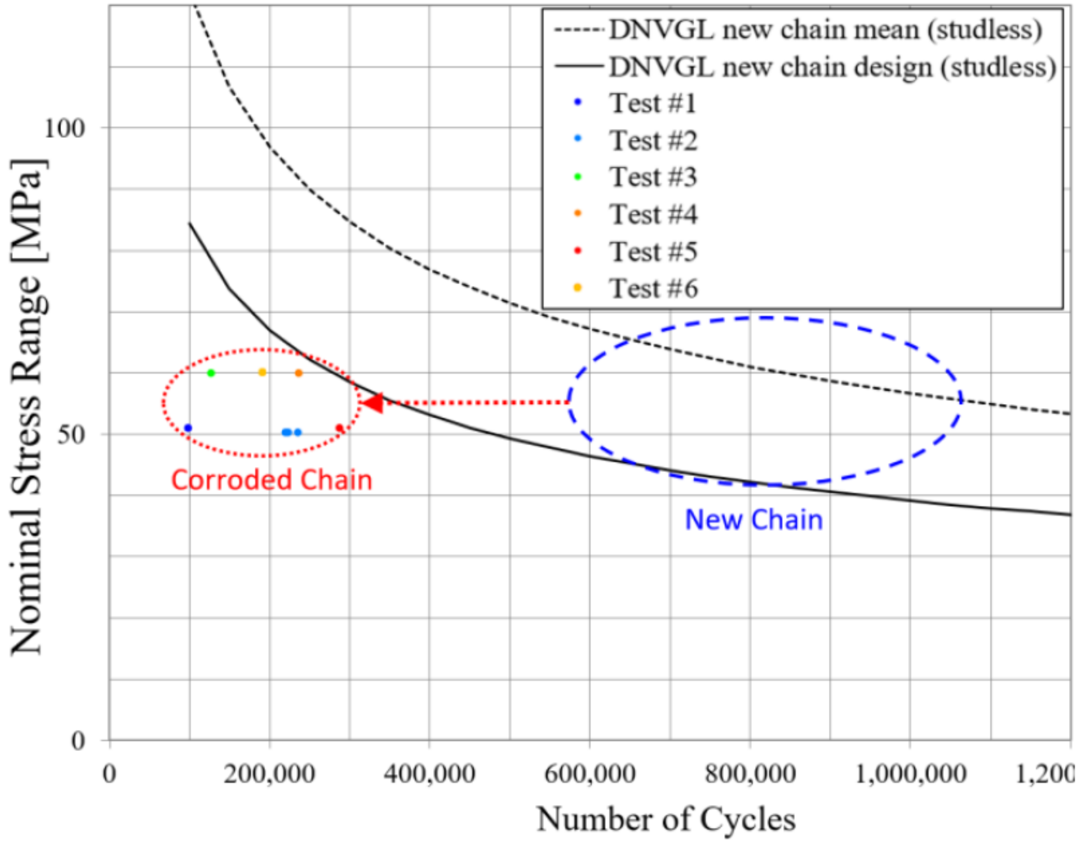
- No significant difference between vendors (Ramnäs / Vicinay / Hamanaka)
- Non-fatigue cracks are blunted

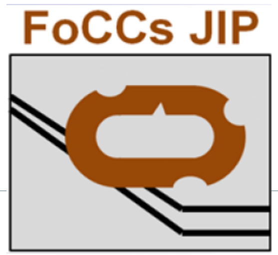
- NOTE! Limited material loss in the tests, i.e. no significant diameter reduction

Corrosion effect to fatigue capacity

- Observed in the Equinor tests
  - … but in combination with lower mean load
- Confirmed by the Fatigue of Corroded Chains JIP/JDP (FoCCs)
- Fatigue capacity loss is significant higher than explained by diameter reduction
- Surface condition is the key factor on fatigue capacity reduction

- NOTE! Effect of combined surface condition and corrosion loss is not studied





OMAE2019-95618

Corrosion effect to fatigue capacity – why?

- In general rough surface has faster crack initiation
- Mooring chains have protective residual compression at surface (fatigue hot spots) due to manufacturing process (heat treatment + proof load)
- Pits, scars and light corrosion significantly increase local (hot spot) mean stress and stress range

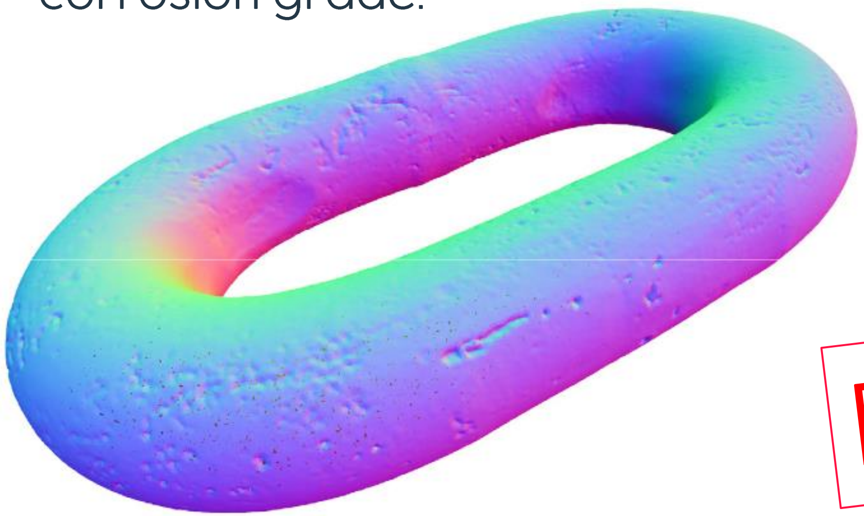
- Corrosion effect is very difficult to model by FEA, as initial geometry and residual stresses needs to be known, and actual corrosion loss must be known to find new residual stress condition.

Relevant work/papers:

- **Perez et al:**
  - Demonstrated (by FEA) protective shell of compressive residual stresses from heat treatment and proof load:
- **Principia (FoCCs study):**
  - Demonstrated significant stress increase with slight corrosion and pits.
- **Zarandi et al (Lifemoor):**
  - Confirmed the complex residual stresses by neutron diffraction

Corrosion effect to fatigue capacity - how to assess?

- Corrosion surface condition grading scale has been developed.
- Corrosion grading scale used in statistical analysis
- Computer algorithms assessing 3D scans has been developed to set corrosion grade.



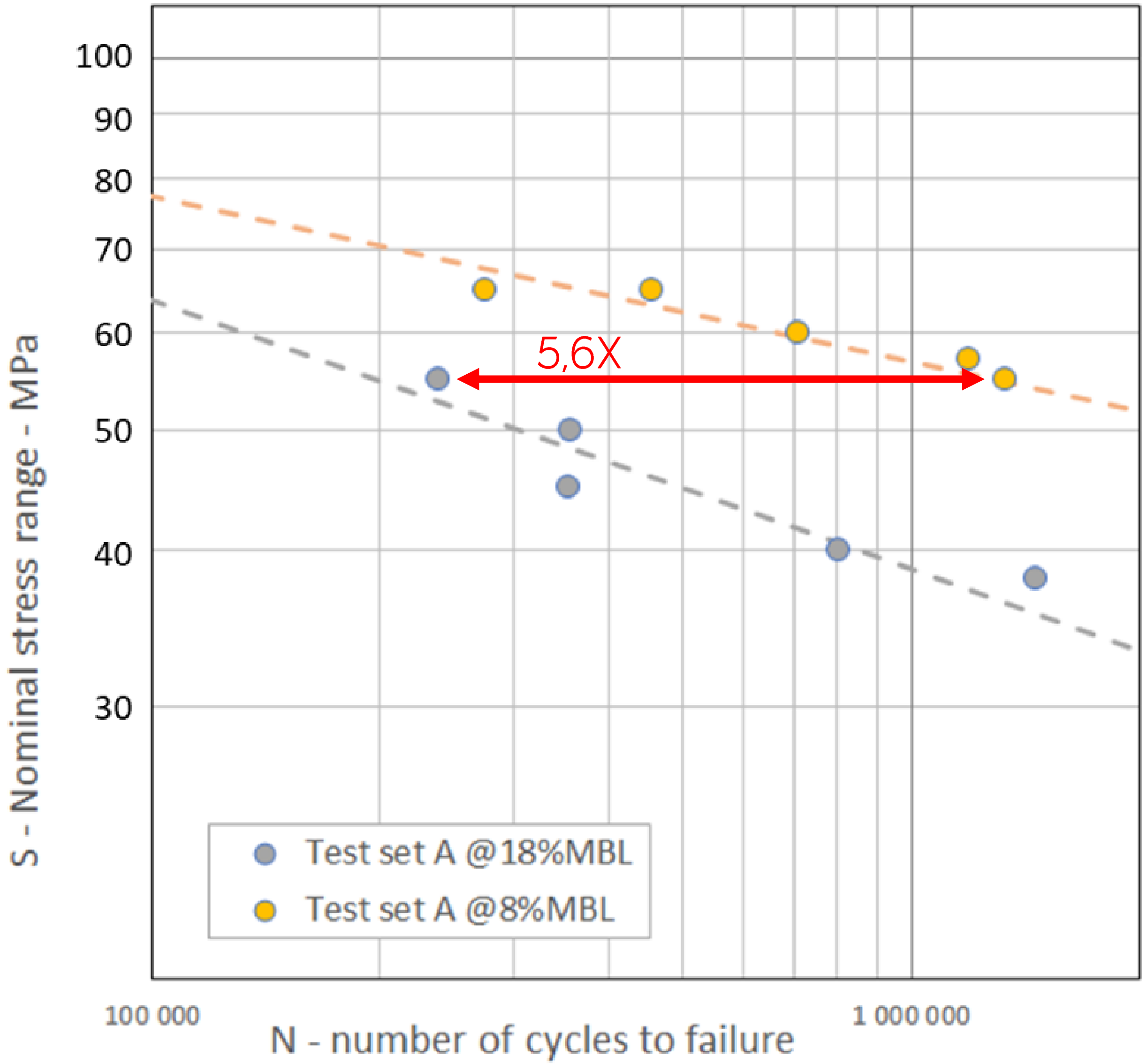
Category	Corrosion condition description
1	New chain and/or only mild corrosion.
2	Some scattered local corrosion (pitting), less than 1 mm deep.
3	Larger areas affected, local corrosion (pitting) around 1 mm deep.
4	Large area affected by pitting, 1-3 mm deep, the deeper sharper in nature.
5	Severe and widespread pitting, up to 4 mm, but somewhat less than for category 6
6	Severe and widespread pitting, 3-6 mm
7	Severe and widespread pitting, 3-6 mm and deeper. Sharp and deep pitting.

DIFFICULT!

OMAE2022-79649

Mean load effect to fatigue capacity

- A significant effect of mean load is observed
- Latest tests performed on ONE chain at both high + low mean load:
  - 5 tests @8%MBL
  - 5 tests @18%MBL
- Significant fatigue life increase with reduced mean load
- !! Question to validity of m=3 for lower mean loads (especially on corroded chains)



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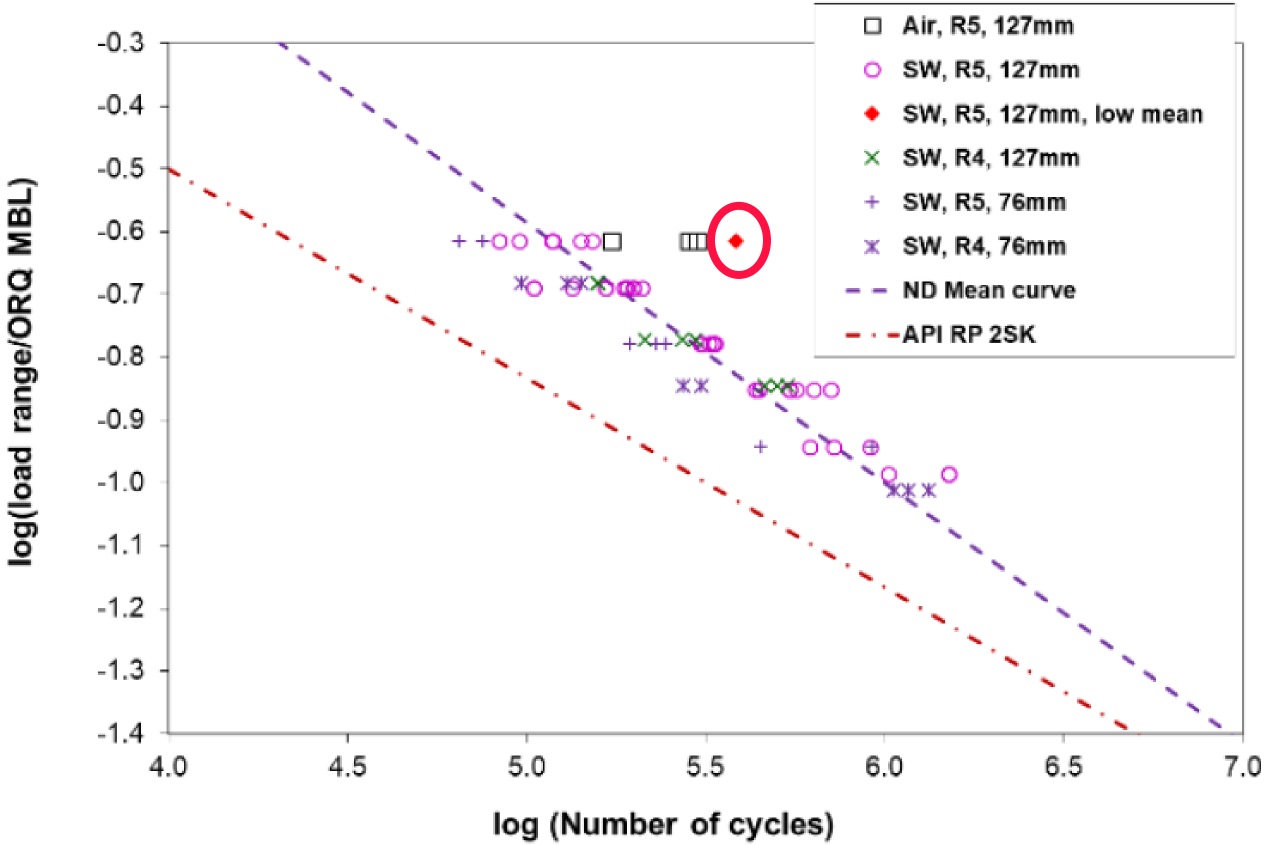
Mean load effect to fatigue capacity – revisiting new chain tests

- ND tests 1990's: 20%MBL
- TWI tests ->2019: 20%MBL + 1x 10%MBL
- Vicinay tests: 7-15%MBL

- Mean load effect for new chain (ND+TWI+Vicinay) derived by Fernández et al (OTC-29621-MC)
- Mean load effect for new and used chain by Lone et al (OMAE2021-62775) and DNV (OMAE2022-81465)



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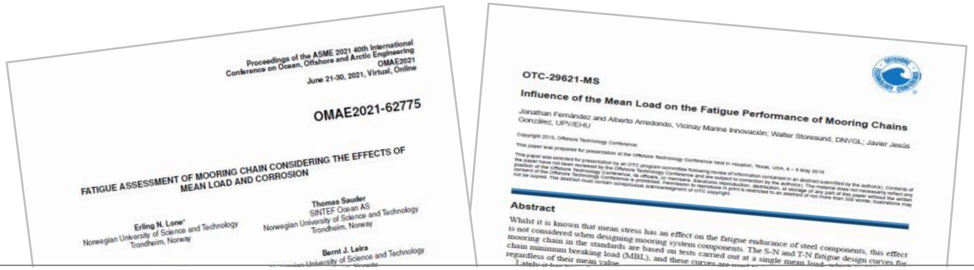


New fatigue capacity formula including mean load and corrosion condition

$$\log N = 12.249 \boxed{- 0.0507 \cdot \lambda_m} - 0.106 \cdot c - 3.0 \cdot \log S$$

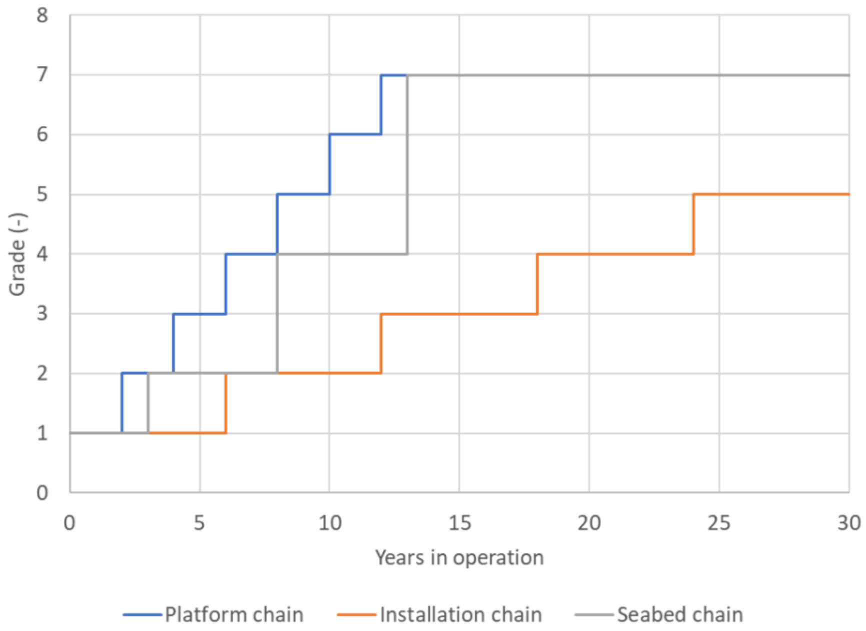
N	Number of cycles
λ_m	Mean load in % of MBL
c	Corrosion condition grade (1-7)
S	Nominal stress range in MPa

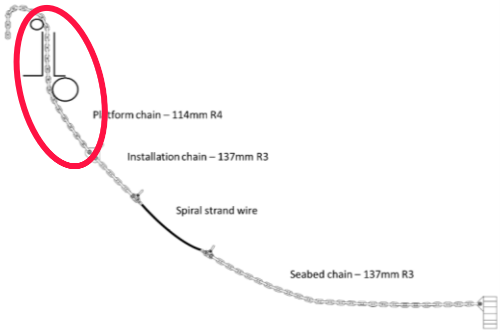
OMAE2021-62775:
Fatigue Assessment of Mooring Chain Considering the Effects of Mean Load and Corrosion.
Lone et al

- «First generation» fatigue SN formula including mean load and corrosion
- Requires new method/model for fatigue assessment
- Requires predicting/knowing corrosion condition development

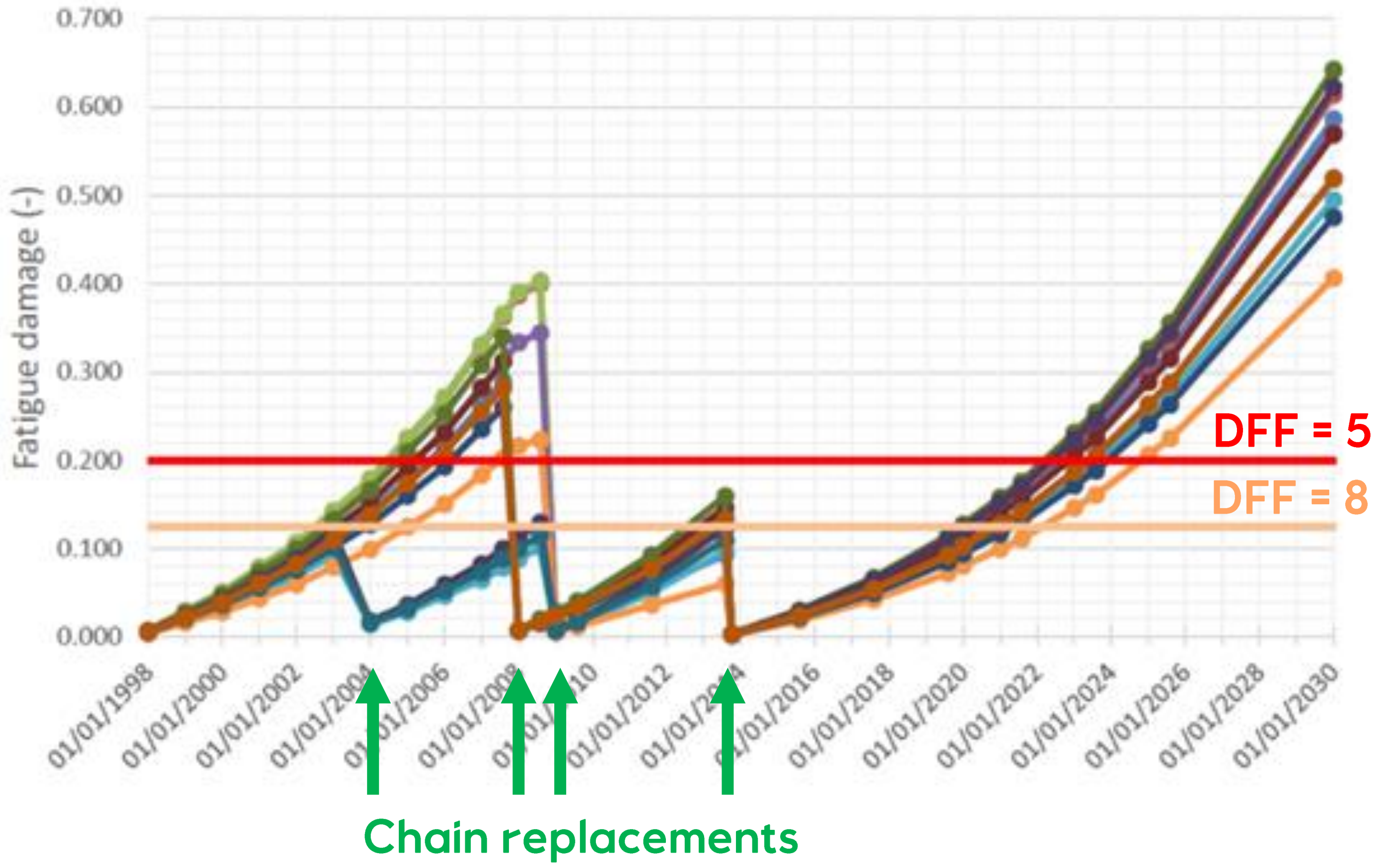
New model for fatigue assessment (I)

- Include effect of mean load
- Assess surface condition development over time
- Accumulate fatigue damage until acceptance level
- Inspect/assess condition to tune surface condition development





AIM-ALE2021-75116



New model for fatigue assessment (II)

- DNV Normoor JIP FLS study:
  - OMAE2022-81465 Analysis of Chain Fatigue Test Data for New and Used Chain
  - OMAE2022-81463 Recommendations for a Fatigue Design Analysis Calibrated Using Structural Reliability Analysis

Equivalent with Lone et al formula

Reccommendation (likely) to be included in next revision of DNV OS-E301

Effect of new knowledge to fatigue assessment in O&G

- Assets with low mean load and limited corrosion may have a significant safe life extension
- Assets with high mean loads may have a reduced fatigue life
- Assets with heavy corrosion may have a significant reduced fatigue life

➡ • New fatigue design analysis can be used for new systems

- Ability to verify actual corrosion condition is the key input to life extension and integrity assessment

➡ • New tools for chain cleaning and inspection needs to be developed

Effect of new knowledge to fatigue assessment in Renewables

- Same formulas can be used for FWT and other floating assets
- Mean load in mooring lines for FWTs can be significantly higher than for typical O&G assets
  - Less fatigue capacity due to high mean load
  - Mean loads may be higher than covered by current test data (i.e. above 20%MBL)

→ • FWT mooring design may be fatigue driven

Further work

- Continue full scale testing of used chain
- Fatigue test chains with significant diameter reduction, especially in combination with pitting ← West Africa asset owners
- Increase mean load in tests (new and used chain) to verify fatigue capacity for FWT
- Develop methods to assess chain condition from subsea measurements / 3D scans ← Lifemoor / Digimoor
- Develop effective chain cleaning and inspection tools
- Verify inspection tools ability to capture corrosion condition (pits, surface roughness, diameter reduction)
    - Subsea 3D scanning
    - Subsea UT (?)

Lifemoor / Digimoor

- Sintef / NTNU competence developing projects
- Collecting and assessing all(?) data on full scale fatigue testing
- Research on the fatigue mechanisms
    - Residual stresses, crack initiation, material behavior
- Development of algorithms assessing corrosion condition grade based on (subsea) 3D scans
- Assessing validity of Miner sum (one amplitude vs variable amplitude)
- Probabilistic integrity assessment
- ++

- Lifemoor project finalized Q2 2022
- Digimoor hopefully to start Q4 2022

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Reference list / further reading

- Reference list from: OMAE2022-79649 Fatigue Capacity Of Used Mooring Chain – Results From Full Scale Fatigue Testing at Different Mean Loads, *Øystein Gabrielsen et al*
- Fatigue reliability of mooring chains, including mean load and corrosion effects, *Erling Lone et al (2022)*
- Analysis of S-N data for new and corroded mooring chains at varying mean load levels using a hierarchical model, *Erling Lone et al (2022)*
- Probabilistic fatigue model for design and life extension of mooring chains, including mean load and corrosion effects, *Erling Lone et al (2022)*
- AIM-ALE2021-75116 Life Extension Of Mooring Chains - Including Effects of Mean Load and Corrosion Condition to Fatigue Capacity, *Øystein Gabrielsen et al*
- PhD thesis at NTNU (2020:337) Multiaxial fatigue analysis of offshore mooring chains, considering the effects of residual stresses and corrosion pits, *Ershad P. Zarandi*