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Materials Testing of Decommissioned Offshore Structures

A report prepared for the PSA programme on Ageing and Life Extension

Originator : Kenneth A **Macdonald**

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0. SUMMARY

The Petroleumstilsynet's (PSA's) interest in ageing and life extension of offshore structures is supporting a number of diverse studies aiming to establish a better understanding of the pertinent issues. The PSA is including in the regulations (from early 2008) proposals that testing of these removed structures be used to fill gaps in our knowledge of ageing processes and degradation mechanisms. This study deals with the question of what should be tested given that decommissioned structures on the Norwegian shelf can be made available for study.

A short study has been made of the possibilities for materials testing of decommissioned offshore structures in steel, and what useful information might be gleaned from such testing with relevance to evaluation of proposals for life extension of similar structures.

Degradation is expected to follow expected trends and mechanisms. The main concerns are expected to be fatigue, fracture and corrosion, and combinations of these. Wider examination is advised to detect the presence of new or unexpected degradation mechanisms not already revealed by in-service problems. Established testing and examination protocols for welded steel structures in the marine environment are recommended but modern test methods in fracture mechanics are also suggested where specifically warranted. Small-scale testing is proposed as the primary means to evaluate in-service degradation. Large scale testing is also proposed to evaluate the overall performance of fatigue design rules and to investigate the effects of weld quality. A strong recommendation is made to make use of actual corrosion profiles for ultimate strength testing.

1. INTRODUCTION

1.1 BACKGROUND

The Petroleumstilsynet's (PSA's) interest in ageing and life extension of offshore structures is supporting a number of diverse studies aiming to establish a better understanding of the pertinent issues. This present study deals with the question of what should be tested given that decommissioned structures on the Norwegian shelf can be made available for study. The background to this initiative lies in the increasing number of applications received for lifetime extension for installations where there exists only limited knowledge of the behaviour of structures and materials beyond their original design life. As more and more structures are being removed, the PSA is taking advantage of this trend by including in the regulations (from early 2008) proposals that testing of these removed structures be used to fill gaps in our knowledge of ageing processes and degradation mechanisms.

A workshop held in spring 2007 dealt with the challenges facing operators working with lifetime extension and the capabilities of R&D organizations to generate knowledge about relevant degradation mechanisms in ageing structures. A subsequent 2-day workshop was held in November 2007 where the various working groups presented their work-in-progress.

The present study aims to identify the important ageing and degradation mechanisms and to establish a framework of materials tests that could be performed on sections of decommissioned structures in order to extend our current knowledge. Of equal importance is to identify those aspects of aging that cannot be resolved by materials testing.

1.2 OBJECTIVES

It was therefore proposed to make a short review of degradation mechanisms in ageing offshore structures aiming to identify relevant mechanisms and which material tests can realistically be expected to provide information useful to lifetime extension projects. The study is, in the first instance, limited to consideration of welded steel structures.

Inevitably, any concession to extend a structure's period of operation beyond the original design lifetime must be based on a combination of both backward - and forward-looking assessments: the historical assessment should include as a minimum some evaluation of the current status of the structure's integrity and how that relates to the original design intent for the present age of the structure; the future assessment should take as a starting point the structure's expended life and the degraded condition of the structural elements and materials.

It is anticipated that mechanical damage, fatigue and corrosion play central roles, however, a broader range of mechanisms will be considered where necessary.

The study also addresses the steps necessary during removal and handling of structural elements in order to preserve material in a suitable form for testing.

1.3 ABBREVIATIONS

BSI	British Standards Institution
CP	Cathodic protection
CTOD	Crack tip opening displacement
DNV	Det Norske Veritas
DOE	(UK) Department of Energy
ECA	Engineering critical assessment
EOR	Enhanced oil recovery
HAZ	Heat affected zone

HISC	Hydrogen induced stress cracking
IIW	International Institute of Welding
LBZ	Local brittle zone
LRFD	Load and resistance factor design
LSD	Limit states design
PSA	Petroleumstilsynet (Petroleum Safety Authority (Norway))
SENB	Single edge notched bend
SENT	Single edge notched tensile

2. STRATEGY

2.1 LIFE EXTENSION STRATEGIES

Life extension is now becoming an important consideration for both industry and regulatory authorities, driven by two main factors. Firstly, advances in enhanced oil (and gas) recovery (EOR) have extended field lifetimes. Furthermore, the development of new finds by subsea tie-back to existing infrastructure has extended the required lifetime for the host structure. Whatever the reason, the lifetime defined in the original design has been, or will soon be, exceeded. In some cases the design life will have been expended (or consumed) in terms of an identified parameter such as fatigue life or corrosion reaching a predetermined criterion; while in others the end-of-life date might be associated with more nebulous concepts of ageing not directly related to any particular structural design parameter, such as anticipated field production life. In both cases, the absence of accurate historical design or as-built data means that a thorough study is required in order to identify the technical parameter(s) that have triggered the end-of-life decision, at least beyond simply reaching a fixed date. A further complicating aspect lies in evaluating the assumed consumption rate of the lifetime limiting parameter, e.g. fatigue, against the actual utilisation, based perhaps on measured loading data or more accurate environmental loading models. This essentially leads to a statement of the current status of the structure's integrity, in spite of any pre-existing notion related to the original design intent for the current point in time.

Given that there exists only limited knowledge of ageing processes, degradation mechanisms and the general behaviour of structures and materials beyond their original design lives, and that we propose to perform testing of removed structures to fill these gaps in our knowledge, it is important to relate the available standardised materials tests to the corresponding design parameter (which in turn is associated with some particular aspect of degradation or ageing).

Inevitably, any concession to extend a structure's period of operation beyond the original design lifetime must be based on a combination of both backward- and forward-looking assessments: the historical assessment should include some evaluation of the current status of the structure's integrity and how that relates to the original design intent for the present age of the structure; the future assessment should take as a starting point the structure's expended life and the degraded condition of the structural materials. It is not always popular to work on the historical aspects as it is often viewed as being wasteful of resources on a phase of life already passed. The life extension work proper is however more readily seen as being positive and productive and it is consequently easier to progress work in this area, in the main associated with actual life extension applications.

The main concerns for the backward looking assessment are: a design review; materials selection records; fabrication/as-built records; inspection records; any repairs carried out; and the loading history (if available).

The forward-looking study must deal with: demonstrating that safe life extension is permissible; accurately determining the present day structural integrity status; and materials (characterisation, and degradation mechanisms).

Some of these aspects are clearly interrelated, e.g. the effect of degraded materials properties on current and future integrity status. Finally and remembering that testing of materials is the focus of attention for this present work, it is also clear that information obtained from such tests has relevance to almost every point noted above.

2.2 LESSONS FROM IN-SERVICE EXPERIENCE

In addition to identifying the important ageing and degradation mechanisms that have led to problems that have required attention throughout the life of installations, the catalogue of difficulties experienced to date by the offshore industry demonstrates that both the extent of known issues can be underestimated, and that unforeseen situations can arise. It is rarely the case that completely new damage mechanisms have arisen, rather unexpected circumstances combine to create difficulties, e.g. the 1980s problems with fatigue at closure welds in jackets; and the more recent leaks from HISC[1] cracking of 13Cr flowlines and manifold hubs in super-duplex forgings.

General aspects of in-service performance were reviewed for the second PSA workshop, included here in Appendix I. The main points raised are:

Modern assessment methods are not always applicable to old structures, materials, or plant
Known degradation mechanisms can cause problems in terms of increased severity, or in combination with other factors.
Criminal activity is not readily predictable
”New” degradation mechanisms are rare
Accurate knowledge of material properties is important

2.3 CONFLICT WITH DECOMMISSIONING OPERATIONS

The very nature of the contracting strategy for decommissioning and removal operations leads to the potential for in-built conflict relating to obtaining structural elements in undamaged condition suitable for detailed examination and testing. Two factors dominate matters: the contractor’s pricing strategy is heavily depend on the value of the scrap steel; and in-field offshore operations are expensive to execute, being highly sensitive to any disturbances to the planned schedule. Taken together, these factors create a general unwillingness to complicate or delay offshore operations in order to extract and protect samples.

Engineering studies relating to design and life extension might direct interest to critical portions of the structure that are perhaps difficult to isolate or reach during normal removal operations. The otherwise most natural or economic sequence of break-up and removal may also be altered. Care beyond normal decommissioning operations will always be needed in handling, transport and storage of samples. All of this creates additional expense to the contractor and this will naturally be reflected in the cost of the work, and so is passed directly on to the operator.

3. DEGRADATION MECHANISMS

The material-related degradation mechanisms known to be active in steel offshore structures and rigid pipelines in both carbon steel and corrosion resistant alloys (CRAs) appear limited to variants and combinations of the three main failure mechanisms:

[1] Hydrogen induced stress cracking

- Corrosion metal loss
- Fatigue crack growth
- Fracture

The last of these, fracture, should be considered as a degrading mechanism for the structure in that in a structure with redundancy, load shedding effects due to loss of joint stiffness may lead to accelerated degradation (e.g. corrosion or fatigue) elsewhere due to increased stresses.

Other materials-related factors with the potential to influence degradation and failure are.

- Embrittlement (reduction of fracture toughness) e.g. cathodic protection (CP) generating hgydrogen)
- Work hardening (overload)

The latter may rise from overload or impact events where the underlying material tensile properties are altered (normally increased yield strength and hardness and reduced remaining ductility).

Structural degradation (as distinct from the material changes noted above) may occur due to mechanical damage by impact or collision. Complex situations exist due to combinations of defects (metal loss – gouges), geometry changes (stress concentration at dents) and altered material tensile properties (work hardening).

Repairs might either be considered as a degradation mechanism or an improvement technique, depending on the nature of the remedial actions. Adequately controlled weld repairs may reinstate the original life expectancy, but a welded repair of damage where no weld existed before would require special attention. In a similar vein, other types of repair such as a grouted clamp might also require detailed scrutiny. Some structures also receive special attention during operation such as the application of fatigue life improvement techniques (e.g. Veslefrikk) and these would need to be taken account of.

4. MATERIALS TESTING

4.1 SMALL-SCALE TESTING

In terms of establishing a framework of potentially useful material tests, this section lists some strategies and appropriate tests available in national, international and company standards and codes. Testing of full-scale structural specimens offers some unique advantages and these are discussed in Section 4.2.

The range of materials testing that is possible falls into four principal categories:

1. Measure changes in material properties directly related to degradation mechanisms
2. Examine or test for either new degradation mechanisms, or unexpectedly significant combinations of known ones
3. Supplementary tests for material properties (of these older materials) that are now known to be important, e.g. variability in tensile properties
4. Applicability of modern design guidance and testing to older materials

4.1.1 General materials testing

Changes in material properties
Degradation will be detected by either failure, or visual and metallurgical examination, looking for evidence of cracking, corrosion, changes in properties (embrittlement, loss of

ductility etc.). The only method available to directly quantify the effect of degradation after a period in service is to repeat the original programme of mechanical testing looking for deviations. The main markers in such an exercise are tensile properties (strength and ductility), hardness, fracture toughness and corrosion resistance. Once found, newer and more accurate methods can be used as the basis for predicting future behaviour in the context of life extension studies.

Specific studies based on measuring hydrogen concentrations may also be needed where there is suspicion of related embrittlement or cracking.

Repeat weld qualification is proposed, supplemented by the normal suite of fracture mechanics testing performed for engineering critical assessment (ECA) and with additional SENT testing on a case-specific basis.

Tests for new degradation mechanisms
In this category, testing is to a great extent dependent upon evidence new or aggressive combinations of existing failure mechanisms being found. In general, the normal material parameters enumerated with tensile, hardness, fracture and corrosion testing will be sufficient to characterise degradation, particularly when supplemented by metallurgical examination.

Supplementary or new tests
Modern design standards increasingly make use of load and resistance factor design (LRFD) and limit states design (LSD) formats, both of which were either unavailable or not sufficiently established at the time of the original design. The probabilistic nature of these design methods places considerable importance on understanding the inherent variability of cardinal material properties such as yield and tensile strength, rather than using single characteristic values of specified minima. Although central in structural design, the significance of variability of tensile strength also affects important details such as overmatching of yield strength at welds for example.

We already understand the differences between old and new materials in terms of cleanliness and metallurgy, and the consequent effects upon strength, toughness and corrosion resistance. The original designs and fabrication work were conducted under rigorous controls but valuable information can nonetheless be gained by confirming the tensile and toughness properties actually achieved in practice (in relation to the fabrication codes of the day).

The proposed testing programme is to be extensive enough to generate statistical distributions and includes: tensile tests for parent material and weld metal; hardness surveys; and Charpy impact tests.

Modern tests and design/assessment methods
It is natural that life extension will be argued on the basis of the best available data and this will inevitably involve state-of-the-art test methods. Fracture toughness has seen the most significant advances of any of the mechanical testing methods, particularly in the estimation of constraint. Appropriate tests could therefore involve constraint correction where the (as yet un-standardised) SENT specimen has already seen significant use in pipeline fabrication. Extension of the principles to general structures is certainly possible in appropriate situations.

Caution is required in the interpretation of results and in the assessment of old materials and welds using modern assessment methods. An example is given in Appendix I where the assessment of pipeline corrosion using (modern) DNV RP-F101 methods leads to unsafe predictions for older pipeline materials.

Older welds are likely to contain larger defect populations due to poorer past NDE and possibly lower toughness locally in specific regions, e.g. weld metal and local brittle zones (LBZs) in the heat affected zone (HAZ). Advances in modern welding procedures, welding consumables and steel production mean that although modern specification requirements remain largely unchanged, they are now readily exceeded in practice.

Repeat weld qualification is proposed, supplemented by the normal suite of fracture mechanics testing performed for engineering critical assessment (ECA) and with additional SENT testing where deemed appropriate.

4.1.2 Fatigue

As it is likely that life extension of in-service welded structures will have to be based on the concept of fatigue crack growth from already existing flaws or fatigue cracks, then useful and pertinent data can be obtained by performing fatigue crack growth tests on these older welds. Although the recommended material property data (Paris law constants and threshold values) in present day design guidance were derived from tests on steels (of a similar vintage) when new, calibration of these data with results from similar age steels that have been exposed to service conditions would reveal if any degradation is apparent.

Small-scale fatigue specimens can be taken from nodes at the various hot spots to evaluate remaining fatigue life in terms of S-N data but welding residual stresses will not remain intact. Although attractive from the point of view of reduced cost, this strategy also risks missing existing cracks or misrepresenting captured cracks due to truncation. Welds presenting a uniform profile, such as butt welds in plates, may be less prone to these difficulties.

The effect of weld quality on fatigue strength has received much attention in recent years and much more is now known about the important parameters such as weld process, toe geometry, spatter, cold laps and flaws. Metallographic examination and profile scanning studies would give valuable information about the intrinsic geometry and flaw populations of older welds.

Fatigue testing of welds where fatigue life improvement has been applied in-service would be immensely valuable as current design guidance is only based on improvements applied and tested under laboratory conditions.

4.1.3 Fracture / ultimate load capacity

Several factors relating to the fracture resistance of production welds (in addition to the general topics discussed in Section 4.1.1) can be investigated using small-scale tests. Changes in tensile properties brought about by ageing, overload events or embrittlement / loss of ductility due to environmental effects (including CP) can all be studied using standard fracture mechanics testing. It also seems appropriate to investigate the actual levels of fracture toughness achieved in structural welds in order to evaluate any discrepancies between production and WPQ testing.

The residual strength capacity of a cross section containing corrosion is best determined using large-scale testing (Section 4.2). No proposals for small-scale testing are made here.

4.1.4 Inspection and flaw population data

It is generally the case that present day non-destructive examination (NDE) flaw detection capabilities exceed the quality levels of past inspections. Because the workmanship-based flaw acceptance criteria specified in welding and fabrication codes have not significantly changed over time, but that welding processes and NDE have both improved, it can reasonably be expected that an older structural weld will contain more, and larger flaws, than does a modern counterpart. Life extension has to be based on the condition of these older welds assessed using modern NDE. It is therefore appropriate to statistically evaluate these older flaw populations, based on metallographic sectioning, as is performed for the qualification and verification of automated NDE systems in modern pipeline construction.

4.2 STRUCTURAL OR SEMI FULL-SCALE TESTS

Full-scale structural fatigue testing, or remnant strength testing, of tubular joints would be an expensive exercise, akin to the large international programmes on tubular joints run in the 1980s in Norway and the UK. Although readily justified from a technical perspective, the associated expense is considerable. The principal advantages relate to accurately obtaining figures for: remaining fatigue life; and remnant strength capacity; both from actual structural welds that have experienced (survived) a design lifetime in service. The weakness of this approach for S-N based fatigue design is that the endurance under test is a combination of the total damage accumulated in-service and under test. The latter is known accurately, while great uncertainty is associated with the former. In mitigation, post-test fractography will be able to adequately characterise the extent of any pre-existing service-related fatigue cracking. These features have particularly direct relevance to life extension.

A unique opportunity exists in being able to test structural sections containing real corrosion profiles, both in terms of internal pressure for pipeline systems (burst strength) and the residual strain capacity of structures. The majority of the published data relating to corrosion is based on testing of artificial and idealised (machined) metal loss profiles.

A similarly unique opportunity may exist to examine and test welds where recognised post-weld fatigue life improvement techniques have been applied, e.g. those now recommended by the design advice of IIW and BSI and originally in the DOE guidance notes. The principal attraction here is to be able to test actual welds improved under on-site or production conditions, as opposed to laboratory-performed improvement.

Finally, structural repairs made either by welding or mechanical means are best studied using full scale testing.

4.3 REMOVAL OF STRUCTURAL SECTIONS

The aim of removing sections of the structure would be to extract material and regions of interest (e.g. welds, damage sites, structural details or areas of corrosion) so that inspection and small- or large-scale testing can be performed under controlled laboratory conditions.

Some information will inevitably be lost in the process of removal, such as long-range residual stresses. The aim however remains to avoid mechanical damage and over loading of elements, particularly where fatigue tests will later be performed. Corrosion processes will be less severe out-of-seawater but also any benefit from active CP will be lost. The desire to obtain specific sites may create severe economic or technical problems for the decommissioning operation to such an extent that feasibility is affected.

Where regions of mechanical or corrosion damage and repairs are targeted, care is need to specify (and execute) a cutting plan so that the sites remain intact and are taken with sufficient adjacent material to allow testing.

It seems likely that only a very limited level of influence will be possible on the removal process offshore, particularly where a structure is to be removed in several sections. The practicalities and demands of cutting and lifting operations will clearly take precedence over study work. Effort should be concentrated on removing samples once the structural sections are ashore, accepting that some sites of interest may be lost in the process.

It is advantageous to remove nodes intact where possible as this preserves joints making them available for inspection and either full- or small-scale mechanical testing.

Entry to dry storage under cover should be prioritised, at least for elements of critical interest. Handling and storage of a nature commensurate with important failure investigations is advisable.

4.4 DISCUSSION

Any fatigue testing of small- or large-scale specimens taken from welds extracted from a structure that has been exposed to service loading is always open to criticism based on uncertainty of the balance between expended fatigue life and remaining life tested in the laboratory. Examination of the fracture surfaces will to some extent disclose the level of pre-existing fatigue crack growth, mitigating at least some of this criticism.

The most independent and reliable data available from tests is that for the underlying material properties, i.e. fatigue crack growth constants, and tensile properties.

Unless new degradation mechanisms are detected, the material properties important to degradation in terms of known mechanisms were encompassed in the original specifications and so can be re-checked at end of life. Such known sources of degradation can be adequately resolved using standard mechanical testing and metallurgical examination techniques.

5. CONCLUSIONS

A short study has been made of the possibilities for materials testing of decommissioned offshore structures in steel, and what useful information might be gleaned from such testing with relevance to evaluation of proposals for life extension of similar structures. The following conclusions were drawn from the work:

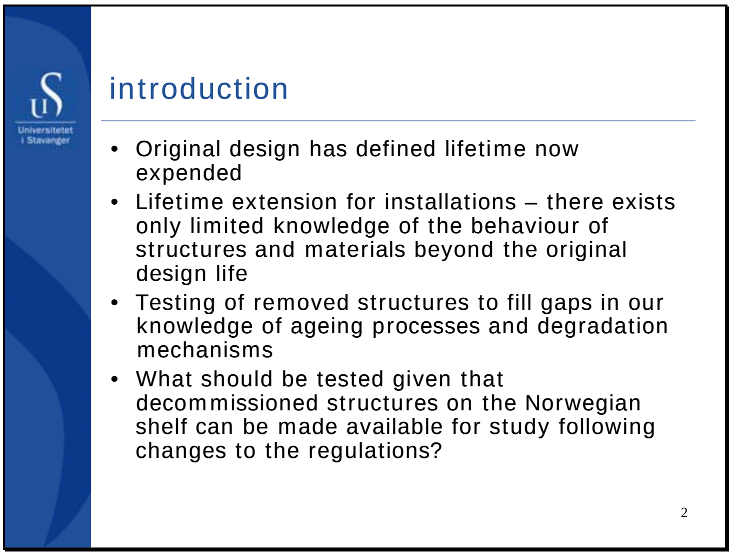
- Degradation is expected to follow expected trends and mechanisms.
- The main concerns are expected to be fatigue, fracture and corrosion, and combinations of these.
- Established testing and examination protocols for welded steel structures in the marine environment are recommended.
- Wider examination is advised to detect the presence of new or unexpected degradation mechanisms not already revealed by in-service problems.
- Modern test methods in fracture mechanics are recommended but on a case-specific basis.
- Small-scale testing is proposed to evaluate in-service degradation.
- Large scale testing is proposed to evaluate the overall performance of fatigue design rules and to investigate the effects of weld quality.
- A strong recommendation is made to make use of actual corrosion profiles for ultimate strength testing.

APPENDIX I

Slides from PSA workshop on Ageing and Life Extension, 20-21 November 2007

Slide 1

Slide 2



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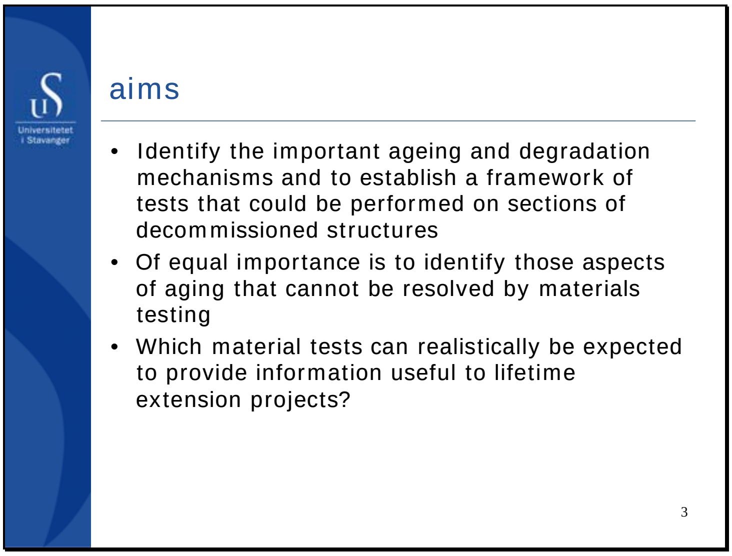

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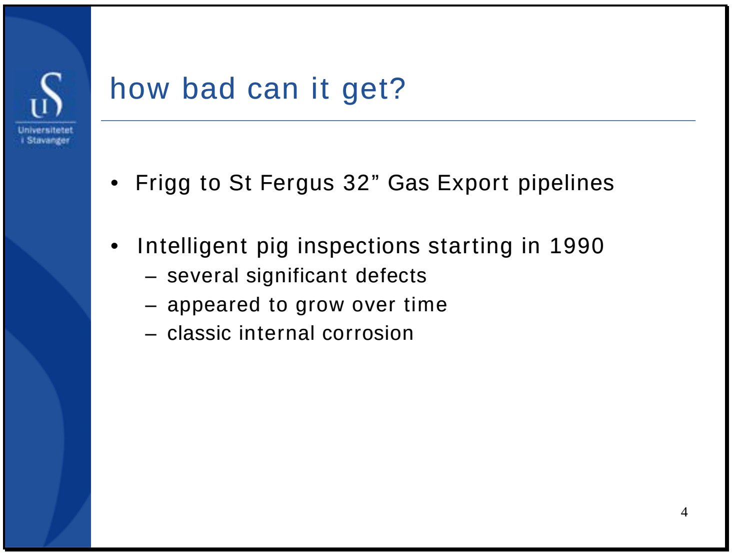

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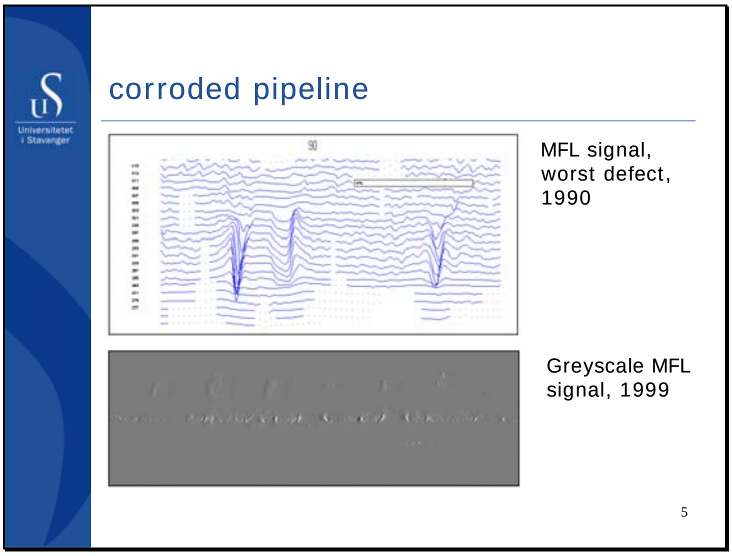

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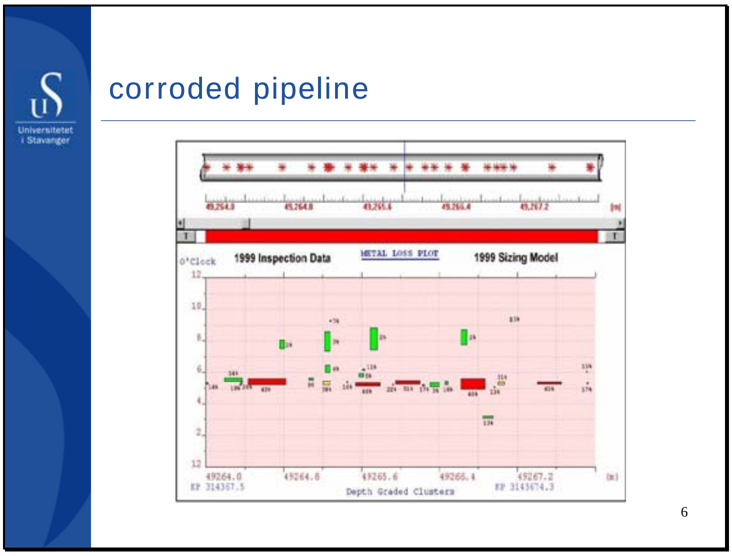

Slide 7

corroded pipeline – growing defects

Inspection Data	Analysis Model	Axial Length (mm)	Circumferential Width (mm)	Depth (% WT)
1990	1990	18	65	38
1990	*1997*	*156*	*56*	*47*
1992	1992	15	63	42
1992	*1997*	*180*	*51*	*46*
1996	1996	250	65	44
1996	*1997*	*260*	*51*	*46*
1997	*1997*	*260*	*50*	*48*
1999	1999	260	50	51
1999	*1997*	*260*	*50*	*48*

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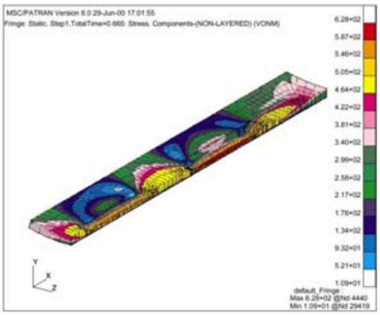
Slide 8

actions



- Stress analysis of corrosion damage
  ⇩
- Reduced MAOP for safe operation
  ⇩
- Cut-out and hyperbaric tie-in of new section

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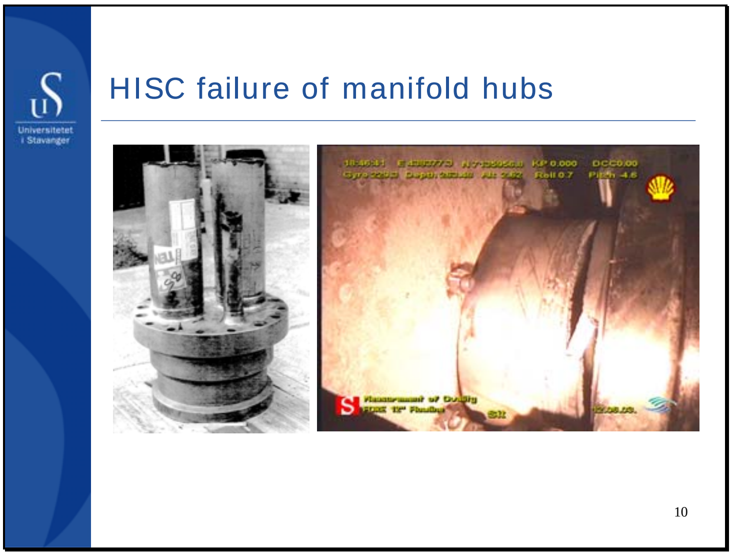
Slide 10

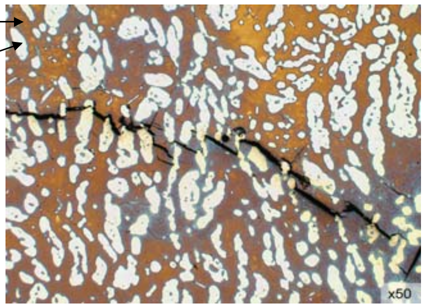


Slide 11

HISC

Ferrite

Austenite



Preferential cracking via the ferrite phase

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Slide 12

HISC

- HISC appears to require a critical combination of stress (residual or applied), susceptible microstructure and hydrogen (CP)
- **Lab experiments** show that materials are not robust
- In contrast, **service experience** is good and we don't yet fully understand why
- Failures have all been non-coated and not at welds

- Science and mechanism are well-understood so why the surprise?
- RP-F112 in preparation – some problems

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Slide 13

closure welds in jackets

- 1980s problem
- Poor single-sided weld quality
- Placed intentionally remote from high stress regions
- Poor NDE at fabrication
- Forgotten during service (not inspected)
- Failures lead to research programmes

- Fundamentals were well-understood so again, why the surprise?

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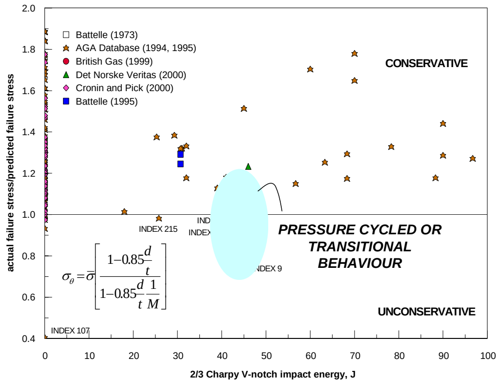
Slide 14

toughness and modified B31G
(RSTRENG 0.85)



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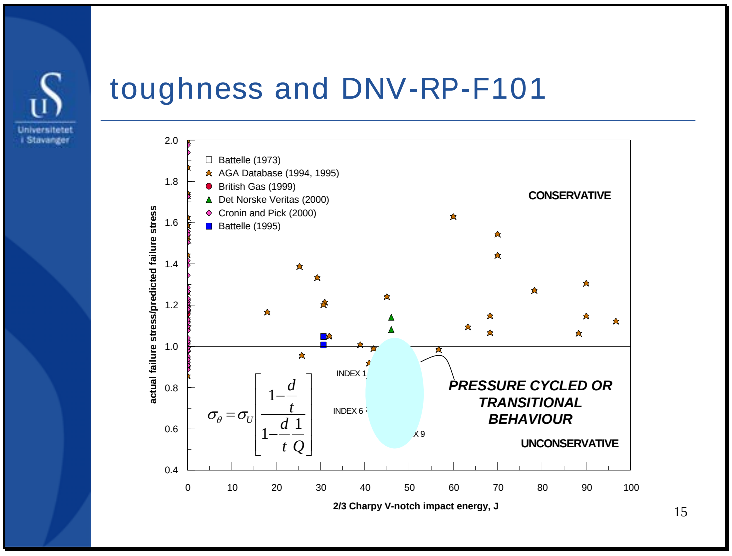

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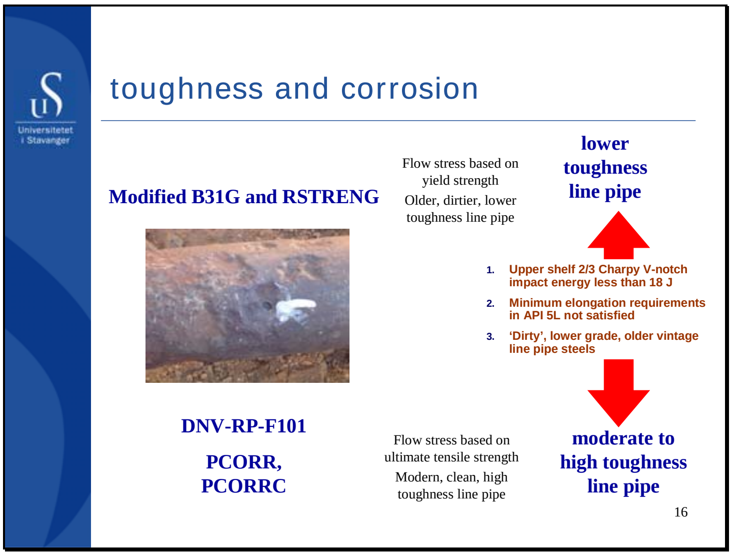

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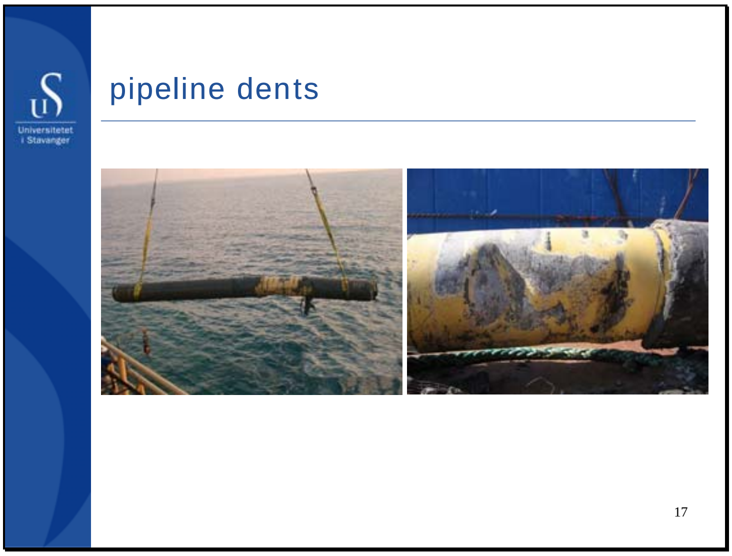

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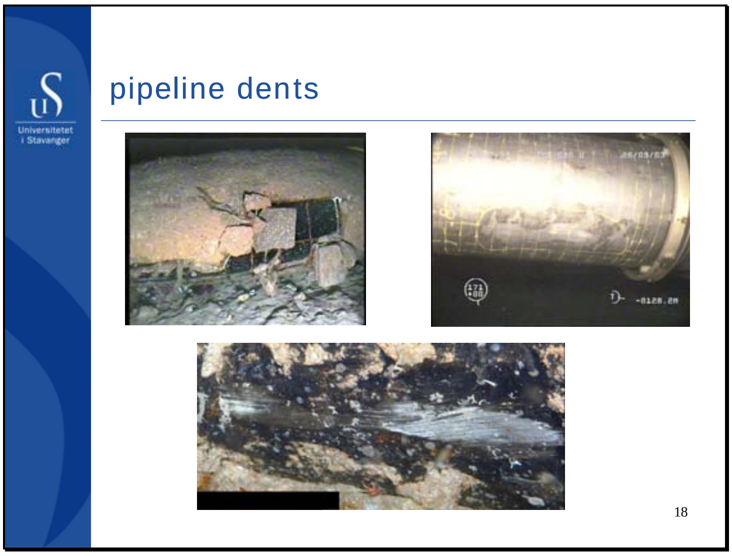

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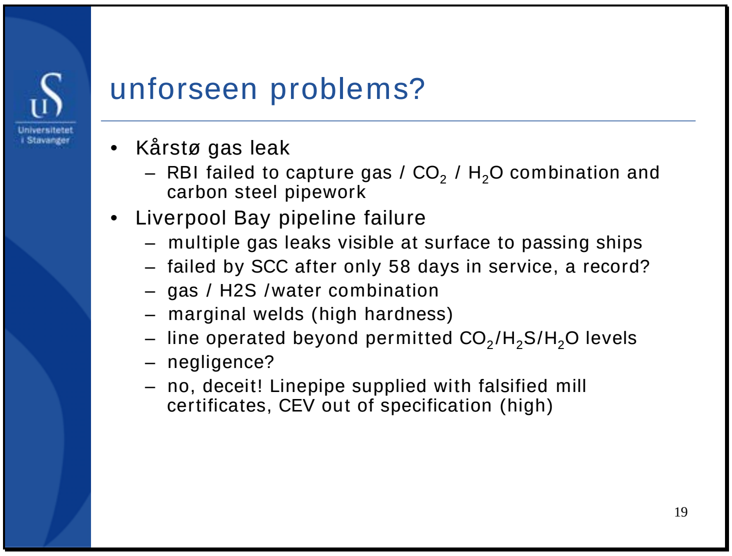

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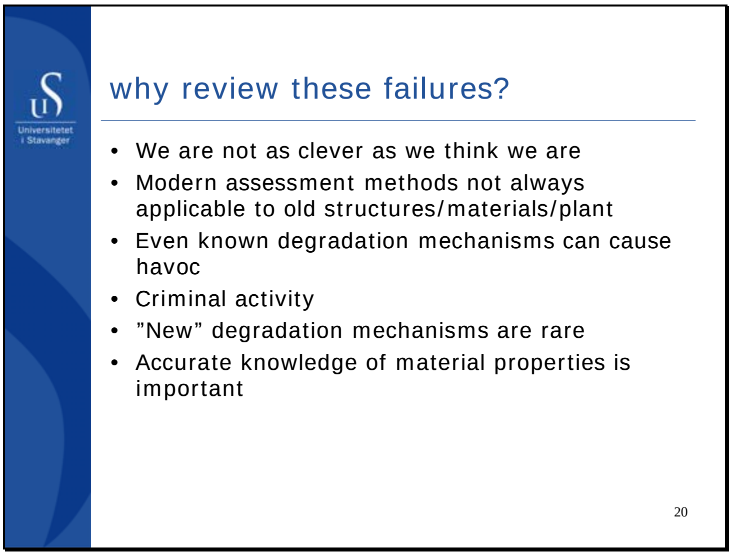

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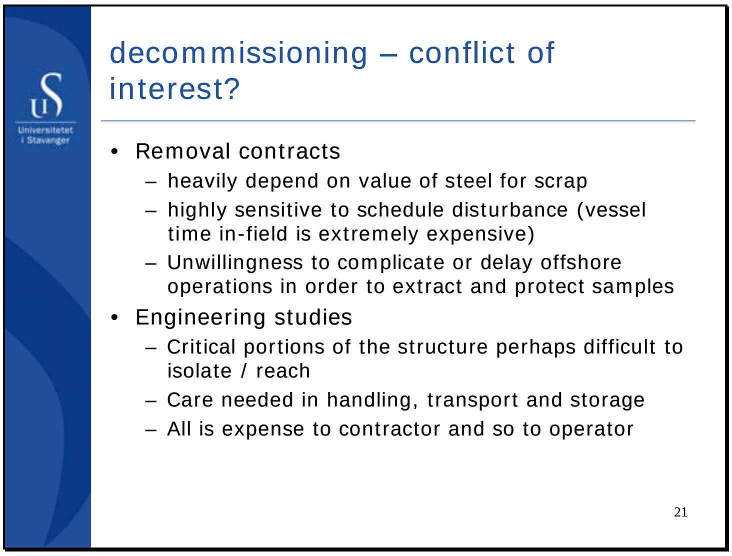

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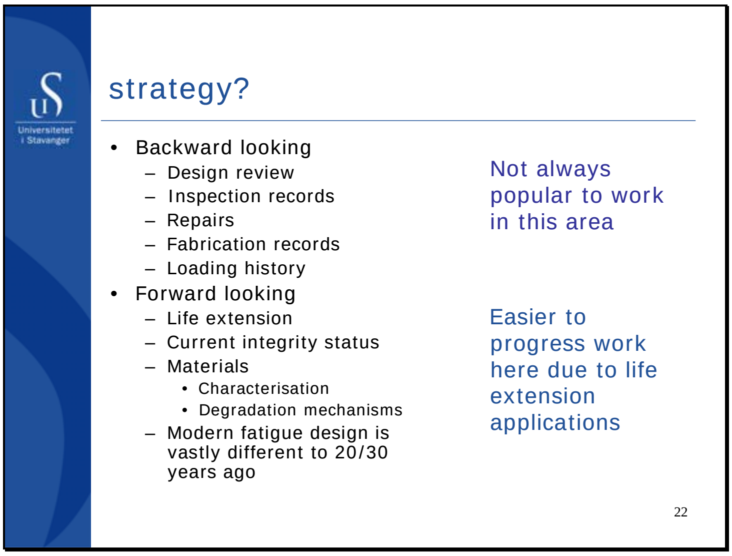

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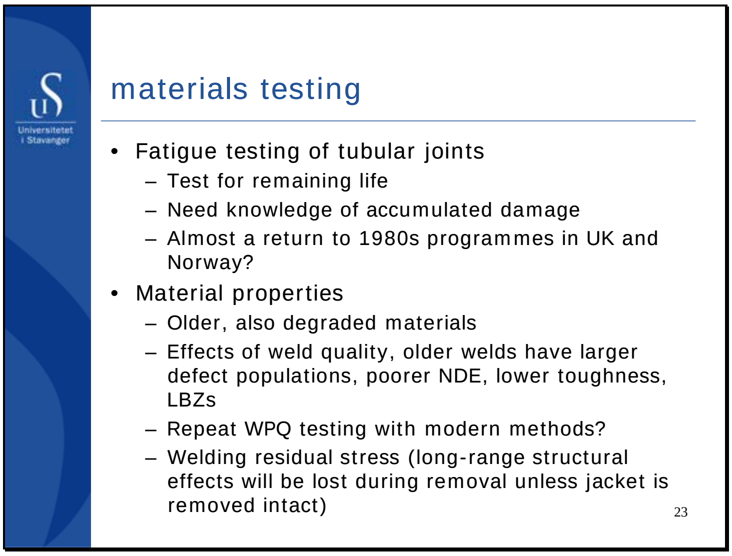

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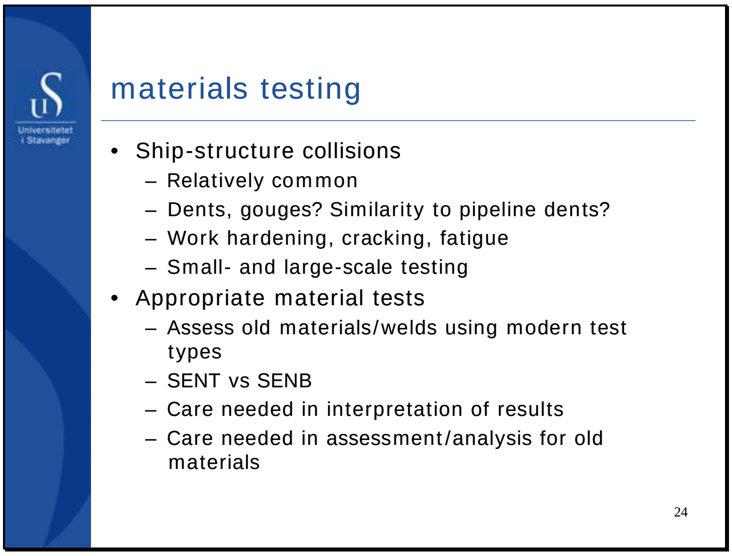

Slide 25

UiS project

- Small, short duration study
- List appropriate material testing
  - What useful information can be obtained for life extension decisions?
  - What corresponding testing is realistic to attempt?
    - Commercial and practical constraints of removal operations.
- Equally important to be clear about what materials testing cannot resolve

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Slide 26

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