Lessons learnt from Oil and Gas: Practical opportunities to increase operability and capability through optimising inspection, engineering and repairs

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1. ABSTRACT

Traditional hull integrity management methods originally designed for trading vessels on a regular docking cycle are sub-optimal for assets that have different usage patterns (e.g. FPSOs moored offshore). Given the constraints around inspection and repair timing, novel and innovative methods have been developed to achieve a more targeted and flexible approach. These methods prioritise engineering investigation and structural risk evaluation over taking an asset out of service for survey and repair.

This paper presents results from several case-studies and details savings and increases in operability achieved. Areas where a tailored engineering strategy and risk-based approach prove advantageous compared to the simpler prescriptive approach of periodical inspections, drydockings and repairs are presented. Furthermore, the regulatory context within Australia from a Class and Statutory perspective is discussed.

The commercial techniques and case studies are then reviewed within a naval context, in particular given the latest “goal-based regulations”, exploring how similar approaches might increase capability and operability of front-line naval assets.

2. INTRODUCTION

Traditionally for marine assets, engineering optimisation of hull structures has been limited to the design stage. During operations hull structure is typically dealt with using a prescriptive rule-based approach [1], [2], [3], [4], [5]. These robust requirements are normally specific to generic vessel categories and loading conditions and based on decades of experience over numerous operational areas. They enable Surveyors with limited asset specific design knowledge to carry out inspections and specify standard repairs when generic acceptance criteria are not met. In the context of a cargo ship or oil tanker trading between ports on a regular docking cycle, or a bulker with long voyages in a ballast condition this approach makes sense. Inspections can easily be scheduled, and cost of repairs is low.

There are however other types of assets which can benefit from a more tailored and flexible approach. This is enabled using increased engineering expertise and alternative regulatory frameworks to optimise hull structural integrity management. This reduces risk and increases asset availability and capability whilst in operation.

This paper describes optimisation in the areas of inspection, engineering assessment and risk mitigation. It also presents case studies demonstrating savings and increase in operability achieved for Floating Offshore Units. Building on this experience this paper also suggests where these techniques may be transferable to the Naval sector.

3. INSPECTION AND MAINTENANCE

Historical approach and background

Inspection requirements for vessels in service have traditionally consisted of periodical survey, with most inspection carried out at regular intervals and most work performed during dry-dock at five-year intervals [1], [2]. Classification Societies have also introduced continuous hull survey [1], [2], whereby major inspections can be staggered across the five-year cycle providing operators with more flexibility. The scope of both these types of inspections remains generic to a vessel class across which there can be significant differences in design detail & operational environment.

Whilst offering robust assurance for hull integrity, these historical approaches will rarely be the most efficient for a specific asset and operating conditions. This is a missed opportunity for the potential to optimise the way risk is managed, increase operational availability and capability as well as reduce cost and avoid unnecessary HSE exposure for inspectors carrying out high risk work.

Types of maintenance and inspections

Five stages of the evolution of maintenance applicable across all industries are shown at a high level in Figure 1. Maintenance approaches can range from mainly reactive right up to a sophisticated system able to predict failures before they arise. For hull structure this level of sophistication could consist of tailored risk-based inspections fed by live data (motions, stresses, load cycles etc.) and managed in a combined data and analysis digital twin.

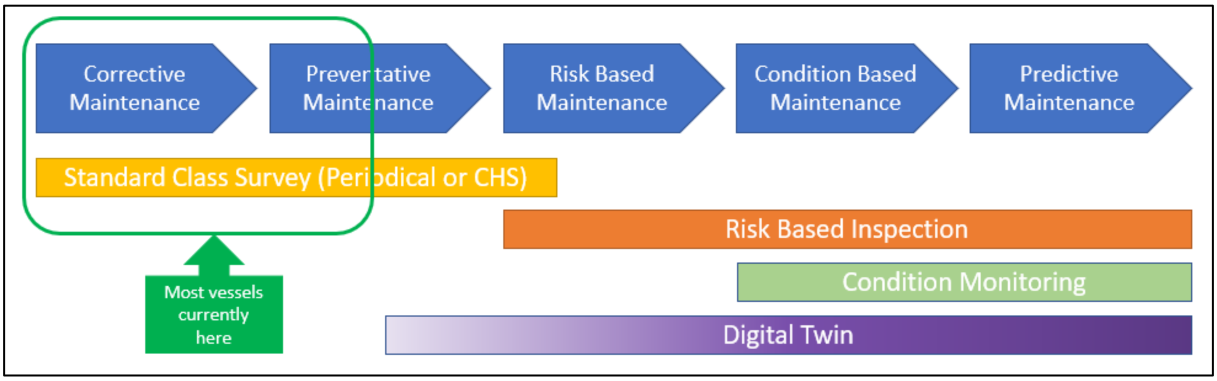

Figure 1 Evolution of maintenance

Although most vessels in Class today are still operating under a corrective / preventative maintenance approach, for floating offshore units (e.g. FPSO and FLNG vessels) Classification Societies have introduced the framework for the development and implementation of Risk Based Inspection schemes [6], [7], [8]. This approach enhances the traditional periodic approach, considering actual degradation mechanisms for each structural element for a specific asset and service conditions. Inspection effort is prioritised based on risk severity, derived from the potential for and consequence of failure. The enhanced understanding of defined risks and failure modes enables a tailored and targeted inspection frequency and scope to be specified to mitigate these risks. For a specific item this may mean more or less inspection than the default prescriptive approach. The more generic wisdom from standard Class inspection requirements is not lost in this process as it forms an additional input to be considered in determining the final inspection scope.

Inspection methods and technology

Most regulations have typically been written around traditional human inspection methods. These generally consist of inspectors physically carrying out visual inspection and non-destructive examination, for example ultrasonic thickness measurements of corrosion, or magnetic particle inspection of cracks.

Technological developments of recent years have led to significant improvements and cost reductions in inspection data capture and deployment technologies. Technologies include high resolution optical cameras (visual / infrared / thermal), 3D photogrammetry, laser point cloud scanning (e.g. LIDAR), phased array ultrasonic testing, pulsed eddy current and time of flight diffraction (TOFD). Many of these can now be delivered using Remote Inspection Techniques (RIT), for example with the use of underwater Remotely Operated Vehicles (ROVs), Unmanned Aerial Vehicles (UAVs) or magnetic crawlers.

Figure 2 Example of a UAV [9], an ROV [10] and a crawler [11] used for hull structure inspection

Importantly, regulatory frameworks now exist for the use of such technologies [12], [13]. Traditional inspection scopes written for human execution however typically need some modification to be suitable for RIT deployment.

The effectiveness and value of such technologies should be carefully considered and depends on the situation, nonetheless their availability for use in hull integrity management opens up new possibilities for the way in which inspections can be carried out and how the risk of defects can be managed.

4. ENGINEERING

Traditional approach to engineering optimisation

Traditionally engineering optimisation is mainly carried out at the design stage. In service inspection, maintenance and repair regimes tend to follow standard prescriptive or empirical approaches without any optimisation.

Under traditional Class Rules, little to no engineering knowledge or effort are required to determine hull inspection scope and frequency, perform inspections and carry out repairs. Acceptance criteria are designed such that a surveyor with no detailed knowledge of actual stress levels for a particular vessel can identify anomalies and specify repairs which are typically ‘like for like’ in accordance with IACS 47 [4].

This system and the rules, regulations and guidance that govern the standard rule-based methodology are based on years of accumulated experience and knowledge and serve the maritime industry well. This approach is reflected in the make-up of engineering support at the design vs operational stage.

Aspect	Design	In service
Personnel	Large pool of dedicated specialist design engineers.	Limited technical support / capability (e.g. one superintendent for multiple ships). Generalists rather than specialists.
Information available	Large volumes of recently created information, authors often still available or within the organisation. Large databases with easy access to critical documents (drawings, design reports, analysis models etc.).	Variable amounts. Sometimes no information is available. Even when available content awareness / understanding may be low (e.g. personnel unfamiliar with difficult to access legacy information).
Optimisation	Significant effort into understanding stress & fatigue, reducing weight, increasing propulsion efficiency etc. Studies and analysis conducted to explore and justify departures from rule minimums.	Rule based acceptance criteria. Repairs to "as built" condition. No design change based on updated service conditions. Limited budget available.
Timescales	Allowances made up front in schedule for analysis and optimisation.	Asset operating schedule drives the quickest solution in a reactive situation.

Figure 3 Comparison between typical design vs in-service engineering support

Engineering optimisation in service

The introduction of additional engineering support in operation enables operators to move beyond the traditional approach. With a better understanding of a specific asset under distinctive operating conditions, inspection scope, frequency and methods as well as remediation of issues can be tailored to better suit the particular needs of that asset.

The optimum level of engineering in support of a particular asset depends on several factors. For example, a simple prescriptive approach may be most appropriate for a young asset, with a long life ahead of it, easy access to a shipyard for low-cost repairs and an adequate allowance for platform downtime. In contrast, for an offshore oil and gas unit which cannot readily proceed to a shipyard, incurs high labour costs, additional safety risks and significant platform downtime for any offshore work, the cost of engineering to reduce the operational impacts of inspection and repair work can be more easily justified. The same can be said of a naval asset for which platform availability and capability are critical. Figure 4 shows some of the tools that can be used to apply increasing levels of engineering sophistication to optimise inspection and risk mitigation efforts in operation. The 'optimum' level of engineering will be different for each asset and depend on many factors some of which are shown at the bottom of the figure.

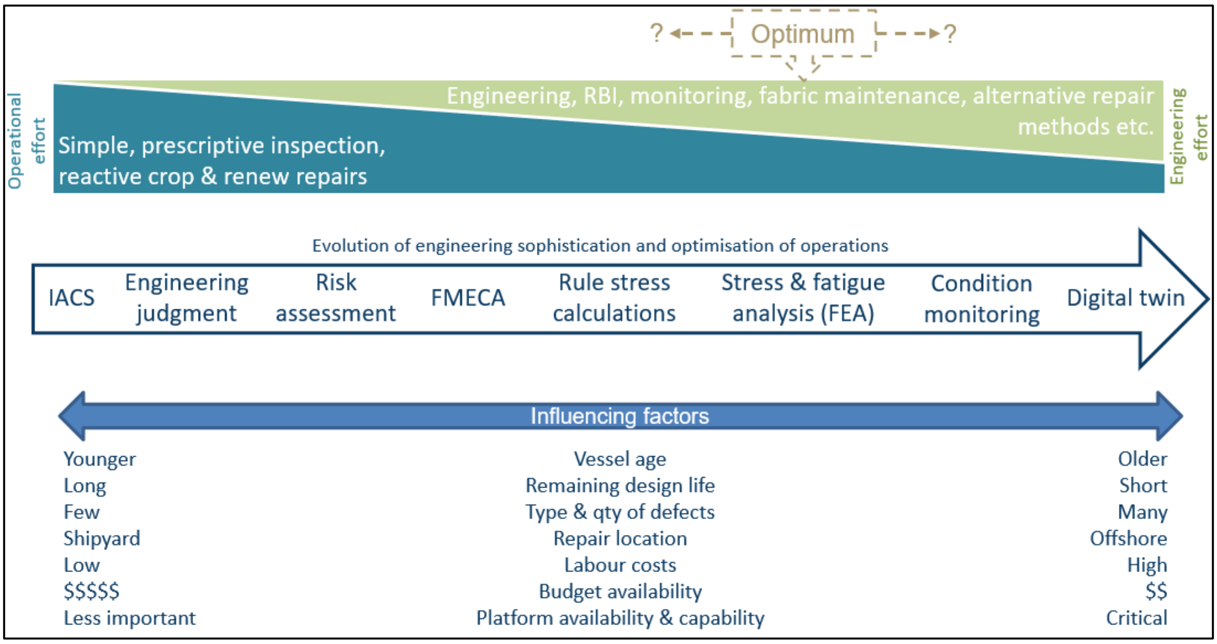

Figure 4 Tailoring of level of engineering depending on influencing factors

IACS: This refers to any repair completed in accordance with the baseline recommendations of the International Association of Classification Societies (IACS). IACS recommendation No. 47 [4] contains a list of recommendations and guidelines for completing the repairs. These are typically 'like for like' also referred to as 'crop and renew' repairs.

Engineering judgement: This is when suitably qualified and experience personnel with knowledge of the asset and its operations tailor a repair or risk mitigation solution. This is normally closely aligned with the original structure as built or IACS 47 [4] and may not involve supporting calculations.

Risk assessment: Using simple techniques, the likelihood and consequence of failure from a defect are assessed to inform risk mitigation and repair decisions.

FMECA: Failure Mode Effects and Criticality Analysis (FMECA) differs from a standard risk assessment in that it considers likelihood, consequence, and detectability of a failure. Where applicable, this facilitates monitoring of defects to become part of a defect management solution.

Rule stress calculations: Using the formulas contained within Class rules and first principles, the capacity of degraded structure with anomalies is calculated. Depending on the defect location and type there can be significant redundancy in hull structures. For example whilst corrosion of a beam may exceed the standard allowable % thickness diminution (typically 20-25% [1], [2]), if the corrosion is localised and at a low stress point on the beam span, stresses and buckling capacity may remain well within allowable limits. A simple stress and buckling calculation can potentially demonstrate that the corrosion is acceptable provided it does not progress any further. In this example arresting the corrosion (e.g. coating repair) and regular monitoring to ensure no further deterioration may be preferable to a repair.

Stress and fatigue analysis: These are more sophisticated approaches than rule-based stress calculations, in that Finite Element Analysis (FEA) and fatigue spectral direct calculation procedures are used to determine structural hot spots and fatigue life [14], [15], [16]. This can be used as part of an overall assessment or for specific anomalies as an input to determine the optimum risk mitigation methodology in a similar way to the example provided for Rule stress calculations above.

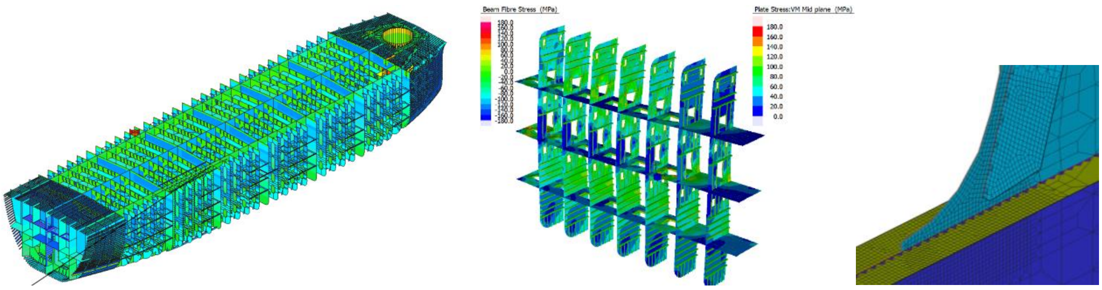

Figure 5 Finite Element Analysis (FEA) models

Condition monitoring: This involves the measurement of live data such as global and local hull strains, wave impact pressures, motions, accelerations, draft and trim, tank levels and metocean conditions to determine the actual material state of an asset as well as loads experienced.

Digital twin: A digital twin is a virtual model designed to accurately reflect a physical object. In the context of hull structures it can be a 'data' twin and / or an 'analysis' twin. The level of definition / data included varies depending on requirements as do the amount, types and frequency of live or static inputs. An example of a hull structure digital analysis twin could be a full ship FEA model updated with live wave conditions from a metocean buoy, live global stress levels from strain gauges, and periodical updates of hull structure with inspection findings (corrosion, cracks etc.). Such a model can provide rapid and up to date understanding of the performance of a hull structure [17], [18], [19].

5. RISK MITIGATION

Under traditional Class Rules, the risk of a failure arising from a structural defect is typically addressed by permanent 'like for like' repair (although there is some provision for temporary repair). The increased level of understanding of hull structural condition achieved using the engineering optimisation techniques described above opens up the following variations of repair or monitoring techniques:

Alternative welded repairs: 'Like for like' repairs may not be the best solution particularly if they do not solve the root cause of an issue (e.g. poorly designed fatigue connection which may fail again). In this case an improved design detail would be preferable.

Cold repairs: These do not involve any welding or 'hot work' and include bonded plates or composite laminate repairs of vessel structure. Regulations exist for bonded steel plates [20], [21] however pure composite repairs still require assessment and approval on a case-by-case basis.

Arrest and Monitor: Where engineering assessment has demonstrated that a corroded structure still maintains adequate strength, that assessment will remain valid provided corrosion does not progress any further. 'Arrest and monitor' typically involves removal of corrosion back to sound metal, grinding sharp edges smooth, repairing the coating and then regular monitoring to ensure the condition does not degrade further. Recent reductions in inspection & monitoring costs through the use of unmanned inspection techniques such as ROVs, UAVs and remote cameras have resulted in this approach becoming cost effective and a realistic consideration for day to day inspections.

Operational changes: Operational limits can be imposed on an asset (e.g. sea state, speed, tank loading etc.) to ensure that the vessel remains within its operating envelope which may be modified to account for structural defects.

6. REGULATORY ENVIRONMENT AND CONSTRAINTS

Civilian statutory considerations

Although at a high level, there is a trend within regulatory regimes to move towards a goal-based approach [22], [23], in practice especially for hull structure, detailed implementation of regulations and acceptance criteria in service are based on and constrained by prescriptive approaches. These are usually centred around a periodical survey [1], [2], [24].

An example of a practical regulatory approach that allows for tailoring within inspection, engineering and repairs is the Australian (civilian) regulatory situation for Oil and Gas vessels as defined within Marine Order 47 [25].

This Marine Order specifically makes provision for deviation from the traditional prescriptive regime that defines the extent and frequency of inspections if the proposed regime is at least as effective as the default prescriptive regime.

An example given is for Performance Based Inspection (PBI) which is acceptable to AMSA so long as it is approved by a Recognised Organisation (e.g. LR, DNV, ABS and BV amongst others [26]).

Naval regulatory position

The nature of Naval Assets and their certification, means that there is a long history of tailoring standards for individual platforms or classes of assets. For many NATO aligned navies, the regulatory position is defined by ANEP 77 [27]. This is a goal-based code derived from civilian international conventions that enables a Naval Administration to certify its assets. Throughout ANEP 77, there are regular references to tailoring including guidance on developing a "tailoring document" within the "standards plan".

Specifically, Part 3 Regulation 6 of ANEP 77 deals with surveys (extract below).

> *"Surveys shall be conducted at a periodicity appropriate to the design, construction, material state and usage of the ship at intervals aligned with those required for merchant shipping regulated by international convention unless determined otherwise by the Naval Administration. In the event that the Naval Administration agrees alternative arrangements for the periodicity for a specific*

ship, the Naval Administration is encouraged to share the particulars and reasons with other Naval Administrations for their information."

Although ANEP 77 does provide a high-level regulatory mechanism for optimising inspections, what it does not provide are detailed guidelines for the practical implementation of this for hull structures.

An example of how a specific administration implements inspections is given by the Royal Australian Navy Publication 4412-4315 [28]. When considering the extract from ANEP 77 above, it can be seen that the RAN approach is more sophisticated than simplistic IACS repairs (see Figure 4). This is facilitated within the RAN guidance as the risk assessment of defects is specifically codified. However, the full range of techniques available to optimise inspections and repairs are not quoted or codified.

Class rules including Naval Class

In general, when considering optimisation of physical repairs, alternative repairs are accepted under traditional Class Rules provided that any proposed alterations to hull structure are approved by Class and are to the satisfaction of the attending surveyor.

When considering optimisation of inspection periodicity, within LR Naval Ship Rules [24], although alternative arrangements for survey periodicity of structure will be considered "upon request", no detailed guidelines are given as to what evidence needs to be provided for any such change. This reflects the approach taken within the ship rules. It should be noted that for items covered by Machinery Class Notations, there are well established rules and procedures around implementing Reliability Centred Maintenance or other forms of condition monitoring.

Overall, there is some leeway within regulations to deviate from prescriptive approaches. One example is where at surveyor discretion the extent of ultrasonic testing can be reduced for structural coatings that are in "good" condition [29]. Others include using "surveyor discretion" and adopting "temporary repairs" [1], [2], [6]. There are also clauses within LR Ship and Offshore Rules [1], [6] allowing original scantlings to be changed. It is also possible to defer repairs using defect criticality assessment methods such as FMECA to demonstrate the effectiveness of any alternative risk mitigation measures (refer Section 5).

Explicitly, if the LR Offshore Rules are considered [6], Part 1 Chapter 6 provides specific "Guidelines for Classification using Risk Based Inspection Techniques". Also available is a guidance note for "the risk-based inspection of hull structures" [7]. This provides a clear framework and a route to approval with a purpose written set of regulations.

7. CASE STUDIES

Case study 1: FPSO Risk Based hull inspection regime

FSC were engaged to develop a Risk Based Inspection (RBI) regime for the hull structure of an ageing FPSO. This AFRAMAX tanker originally built in 1981 and converted into a disconnectable FPSO in 2008-2009 had been operating in Australia under a periodical inspection regime since conversion. The vessel had recently completed Special Survey VIII in 2020.

The driver for change was the fact that unless any optimisation were completed, the survey regime would fall under the IMO ESP code requirements [3]. For a vessel of this age, this would require a full 5-year special survey scope to be carried out every 2.5 years instead of every 5 years; a doubling of the inspection requirements. For trading vessels which dock at regular intervals and have limited ability to apply more sophisticated inspection regimes, this is an appropriate way to ensure the increased integrity risk that comes with vessel age is accounted for. However, for an FPSO the operational implications of this requirement are a significant increase in personnel safety risk (many inspections involve human entry to confined spaces and working at height), and the significant cost of offshore inspections including knock on effects on production uptime.

A Risk Based Inspection regime was therefore developed in accordance with LR guidelines [7]. A high level flow chart for the development of the RBI is given in Figure 6. Initially a detailed RBI basis of design was developed to collate historical data, verify sufficient technical knowledge and identify areas where more work (e.g. inspection or analysis) was required to develop a fit for purpose RBI plan. Subsequently additional analysis was carried out, and condition prediction reports created. These summarised all key insights from past data, current condition as well as predicted condition for corrosion, buckling, cracks & fractures, fatigue and stress. These reports as well as input from key stakeholders during the RBI workshop formed the key inputs to the qualitative risk assessment. Using the operator's corporate risk matrix, defined inspection and monitoring methods and inspection frequency tables, suitable inspection and monitoring scopes and frequencies were determined to mitigate identified risks to an acceptable level whilst working within operational constraints.

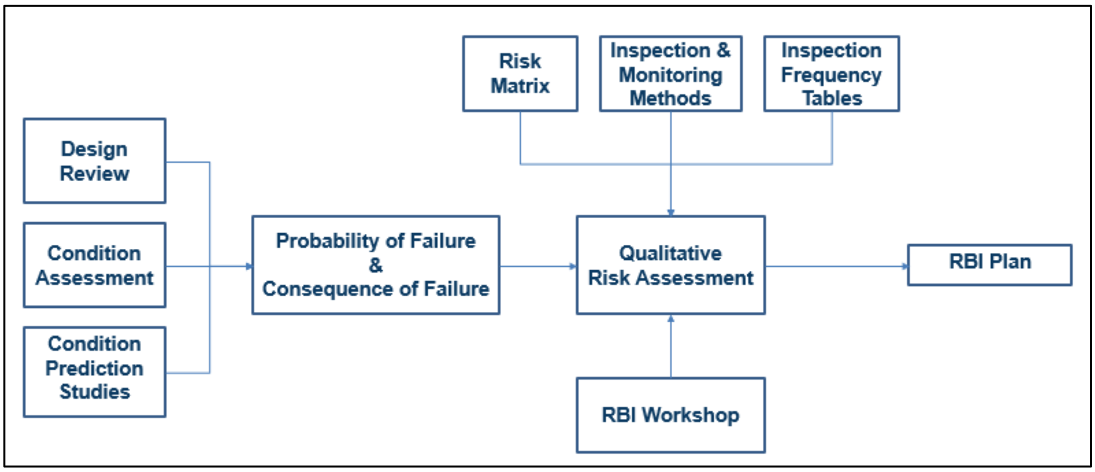

Figure 6 Simplified hull RBI development process flowchart

The resulting RBI plan provided the operator and Class with a far better understanding of the specific risks applicable to the asset. This understanding was founded on an extensive and clearly documented evidence base, enabling tailored inspection scopes and frequencies to be implemented, increasing asset availability, and significantly reducing risk and cost.

Inspection frequency for most tanks was halved compared to ESP requirements. The clearly defined inspection scopes for each tank directly address the relevant risks. This increases the efficiency of the actual inspections in terms of the value of the data obtained. Formal costs savings are not available, however the following provides an order of magnitude. Considering 21 cargo oil and water ballast tanks and an average offshore inspection cost of approximately $0.5M per tank, savings over five years are of the order of $10.5M. Some tank inspections also required production shutdown, therefore additional production related savings in addition to the quoted number were also achieved.

Case study 2: Operational availability increased through drydock schedule reduction

The emergence of a significantly higher level of hull structural anomalies than expected during the Special Survey inspection carried out offshore for an FPSO lead to hull structural repairs becoming the critical path activity for the subsequent drydock campaign. This risked delaying the planned date for return to field and production startup. FSC applied a combination of inspection, engineering and risk mitigation optimisations to achieve significant reductions in shipyard repair scope. This took hull structure off the critical path and brought the schedule back on track.

Over a 22-month period, in parallel to the offshore inspection and drydock campaigns, several of the techniques discussed earlier were employed.

Figure 7 shows the total steel renewal weight on completion of all inspections if a standard IACS 47 [4] 'crop and renew' approach was taken (248t). The impact of the optimisations that were carried are shown in the green 'waterfall' steps.

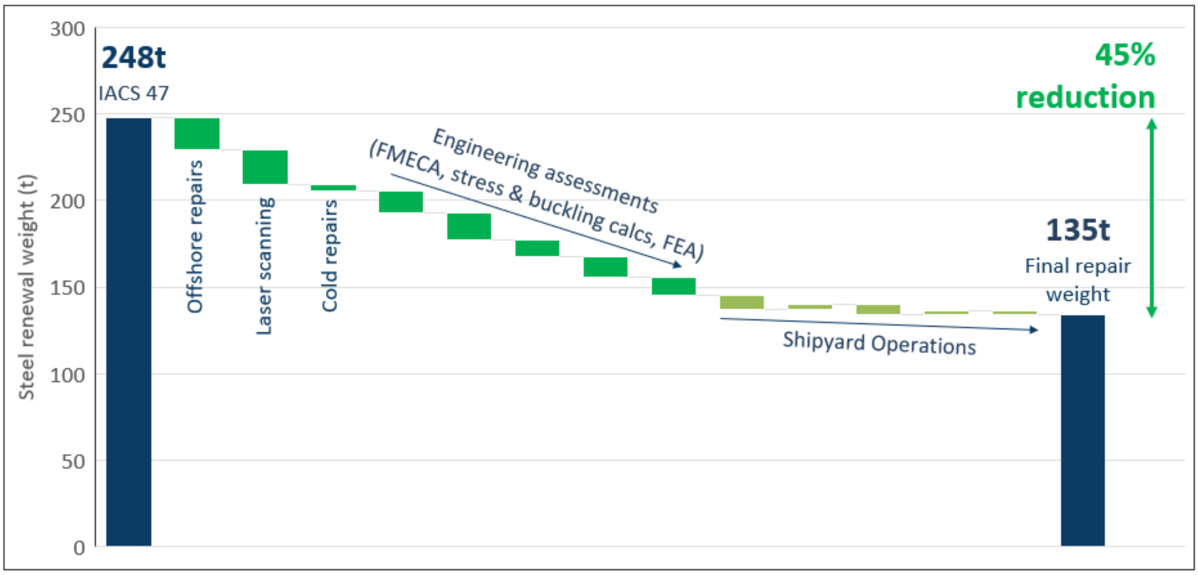

Figure 7 Inspection and engineering optimisation – repair steelweight waterfall chart

The final repair steel weight was reduced by 45% compared to that required with simple application of IACS 47 requirements, with a corresponding reduction in manhours, cost & shipyard schedule of approximately 30-40%. This clearly demonstrates the benefits of the approaches described in this paper.

Case Study 3: Naval patrol boats – unlocking maximum value from stress monitoring

To better understand and manage hull structures for the new RAN Cape Class Patrol Boats (CCPBs), a study was carried out into the implementation of a fit for purpose real time hull structural health reporting system.

The challenge in implementing such a system is not only what data to measure and what equipment to install to collect that data, but how the data will be used, and integrated into the wider hull and overall vessel integrity management system. This includes looking at how maximum value can be extracted from the data by enabling findings to feed back into the fleet inspection and maintenance programme.

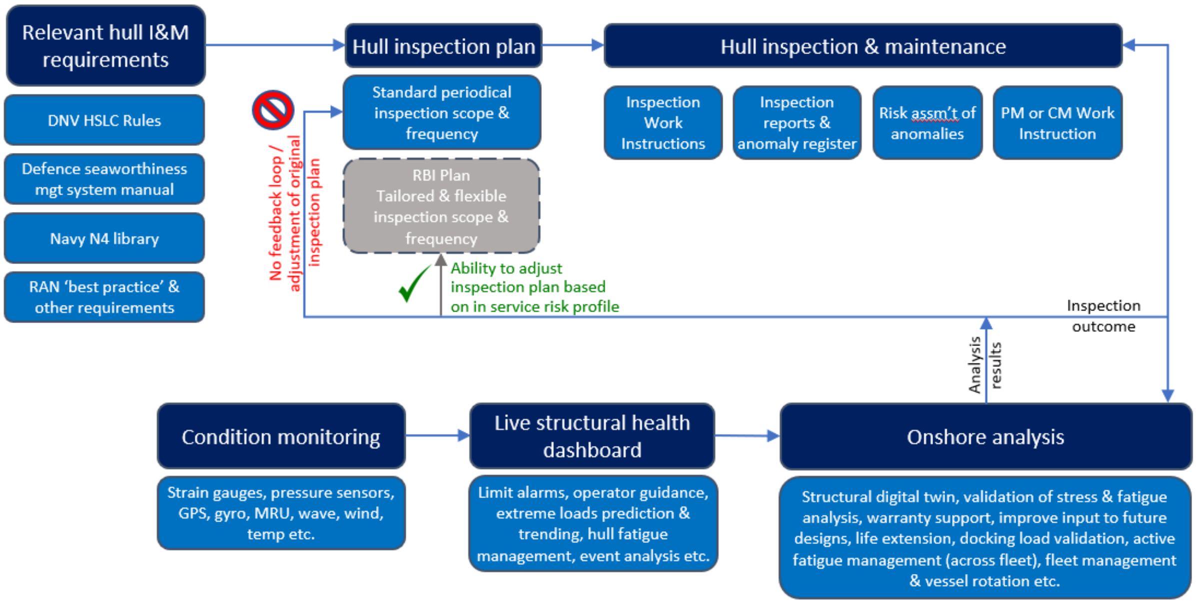

Figure 8 Example hull integrity management framework for RAN Patrol Boat

Figure 8 shows a high-level overview of a potential RAN Patrol Boat hull integrity management framework, under a standard Class / Naval periodical inspection regime. Recording live data such as global stresses, local stresses at known stress hotspots and fatigue cycles can bring significant benefits to the understanding of how an asset is performing, both immediately to the crew, but also back onshore with a wealth of potential uses for the information.

Under current DNV HSLC [5] and RAN [28] inspection frameworks there is no clear guidance for the use of this knowledge to influence inspection frequency and scope. To unlock maximum value from the data a condition monitoring system provides, an alternative regulatory framework for inspection is required (refer Section 6).

If an RBI plan can be used in lieu of standard Class and Naval inspection scopes, that will bring two key benefits to the CCPBs. The first is that initial inspection scope and frequencies can be tailored to match the specific risk profile for the vessel based on design assumptions. The second and arguably more significant is that risk profile changes through the life of the asset informed by live data on stress levels and environmental conditions can be used to tailor inspection requirements. For example, where stress levels or fatigue cycles are lower than design assumptions and inspection data show no issues, it may be possible to extend inspection intervals for certain high stress or fatigue critical details. Conversely if the fluid properties or temperature, or indeed the inspection findings (e.g. coating breakdown) for tank indicate a higher corrosion risk, inspection frequency and scope may require increasing to ensure the risk is managed.

The flexibility of this mechanism ensures inspections are only undertaken where required, rather than just because a standard prescribes it. Likelihood of failure is also reduced through a better understanding of structural behaviour and the ability to target areas of concern more accurately. Both these benefits as well as lowering overall risk are likely to increase availability and operability of the platform.

8. APPLICABILITY IN A NAVAL CONTEXT: INCREASING CAPABILITY AND OPERABILITY OF FRONT-LINE NAVAL ASSETS.

Similarities between naval and floating offshore units assets that adopt RBI

When considering commercial assets that adopt RBI as compared to Naval assets, both seek customised certification and survey regimes that reflect the vessel's operational envelope. For Naval Vessels this can be highly tailored [23], [27], [28].

Both also normally have a greater availability of engineering resource (in house, subcontracted or otherwise) to support the more detailed considerations of such an optimised approach.

A further similarity is that in both cases assets with long life spans and multiple through life extension plans are being operated.

Situations where Naval Assets may benefit from optimised inspection and maintenance approaches

If it can be shown that a naval asset need not be inspected, or if during an inspection that a particular defect need not be repaired to complete the intended mission, then it may be possible to increase capability and availability. By quantifying the effects of the defect, it may also be possible to avoid any operational restrictions that reduce capability. Or indeed avoid disconnection of mission critical systems to effect structural repairs.

From the authors' knowledge and understanding of existing Naval practices [23], [27], [28], [30] it is suggested that there could be scope to use the same techniques deployed in the Oil and Gas sector to tailor the inspection periodicity and engineering evaluation of structural defects in a systematic way to improve availability and capability. This could be further improved should condition monitoring data be collected and used effectively.

For example, with effective condition monitoring and risk based inspection, a deployed frigate or destroyer may not need to make a long transit to a home port. Instead, it could stay on station at a high level of readiness or put in to a commercial port for far more targeted, shorter and less intrusive maintenance without any increase in risk. Another example could include not needing to disconnect essential parts of the combat system or chilled water system to inspect and repair primary or secondary structure. This could maintain or increase availability of a front-line asset whilst providing evidence that its structural capability has not degraded.

When anomalies do require repair, rather than simply re-instating the 'as-built' detail, an enhanced understanding of risk can enable the repair to be tailored to the latest operational requirements of the vessel considering repair capabilities, location and scheduling.

9. CONCLUSION

Several techniques have been established and proven for optimising the in-service inspection and maintenance of hull structures. As demonstrated in the case studies above, these can deliver multiple benefits for the right sort of asset and supporting organisation.

Engineering optimisation of repair methods and risk mitigation is already accepted by Class subject to review and approval. To facilitate a change from traditional prescriptive inspection and repair regimes, purpose written regulations are required.

Within the Australian Oil and Gas sector the regulatory regime is in place for risk-based inspection with detailed guidelines available and several vessels already operating under this framework.

Within the Naval context, the regulatory regime exists under ANEP 77 [27] to apply tried and tested techniques to optimise the maintenance regimes of Naval Assets. Although in specific cases, inspections and repairs are already subject to optimisation, a more comprehensive and wholesale adoption of regulations and techniques used in the civilian context could provide multiple benefits. These include increased clarity, understanding and standardisation of the methods involved, improved assurance of the asset's ongoing ability to safely deliver the required capability, and more rigorous evidence for regulatory compliance.

In summary a better understanding of the asset's hull structure under a fit for purpose regulatory regime can enable optimisation and efficiency gains in inspection and maintenance. This provides the flexibility required to improve the availability and capability of the platform.

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