TECHNICAL NOTE

TOWARDS A QUALITATIVE-QUANTITATIVE DECISION-MAKING AID FOR FATIGUE LIFE EVALUATION OF NAVAL HIGH SPEED LIGHT CRAFT

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SUMMARY

The Life of Type (LOT) of a naval High Speed Light Craft (HSLC) can be limited by its structural fatigue life. The fatigue life of a ship is influenced by many factors, such as geometry, fabrication quality, the long-term load distribution, and analytical techniques. The complex dependencies between these factors and the fatigue life cause uncertainty in predictions. A lack of understanding of uncertainty can adversely affect the management of LOT risks, resulting in the reduction of availability of the ship and costly repairs. Therefore, improved understanding of the benefits and limitations of different fatigue life evaluation approaches informs the management of risks relating to the ship's LOT. This paper presents the first phase of work in a comparative analysis of different fatigue life evaluation approaches for naval HSLC. The present work involves a holistic data review, codification of the data to reveal key themes, and individual expert comparative analysis of the different approaches. The next phase of the study is also described.

NOMENCLATURE

$\Delta\sigma$	Stress range (MPa)
CDT	Cumulative damage theory
CLC	Capability Life Cycle
CRA	Comparative Risk Assessment
D	Fatigue damage
FEA	Finite element analysis
HMS	Hull monitoring system
HSC	High Speed Craft
HSLC	High Speed Light Craft
i	Interval
k	All stress cycles
LOT	Life of Type
LOTE	Life of Type Extension
n	Number of stress cycles
N	Number of stress cycles to failure
RAN	Royal Australian Navy
SFA	Spectral Fatigue Analysis

1. INTRODUCTION

Defence capability can be defined as 'the power to achieve a desired operational effect in a nominated environment within a specified time and to sustain that effect for a designated period' (Department of Defence, 2017b, p. 85). A major component of operational capability could be specialist military equipment or materiel, an example of which is a naval ship. The phases of the Australian Defence Capability Life Cycle or CLC (Department of Defence, 2017b) are shown in Figure 1. Also shown is a set of generic life cycle phases after Blanchard and Fabrycky (1998). The Life of Type (LOT) of a capability has different descriptions, including the 'design service life' and the 'assessed service life'. The former is the life that the capability is designed to achieve during its in-service phase. The latter is the measured age of the capability based on its material condition and usage (Dow et al., 2015).

Figure 1: Comparison between Australian Defence CLC (2017b) and Blanchard and Fabrycky's Life Cycle (1998)

Recently, Governments have embarked upon enterprise approaches to naval shipbuilding; examples include the Naval Shipbuilding Plan in Australia (2017c), Canada's National Shipbuilding Strategy (2016), and the United Kingdom's National Shipbuilding Strategy (2017). These plans identify the need for navies to acquire more ships and modernise the fleet. The substantial investment in naval shipbuilding demands delivery of value to Governments, highlighting the imperativeness of the sustainment of a capability (relative to the Australian Defence CLC, sustainment is the operating support, engineering, maintenance, supplies and training support required to maintain a capability).

Degradation of the hull due to fatigue can limit the service life of a naval ship (Collette, 2011, Doerk, 2017, Dow et al., 2015). The fatigue life of an engineering structure is defined as the number of cycles of fluctuating stress that a material will sustain before failing. Among the sources of cyclic loads applied to a ship structure are wave action and transient vibration induced by impact loads such as slamming (Hughes and Paik, 2010). For ships constructed of steel and marine-grade aluminium alloys, the fatigue life can be influenced by many factors, such as geometry, fabrication quality, and the long-term load distribution. The complex relationships between these factors and the fatigue life leads to uncertainty in LOT predictions (Mao et al., 2010, Kecsmar and Shenoi, 2004). Risk can be defined as the potential of adverse consequences of an event, and is commonly represented as occurrence probabilities with associated consequences (Sieve et al., 2000). Risks to maintaining the required structural performance of a naval ship can arise from inadequate understanding of uncertainty, and incomplete and imprecise information.

Decision-makers (defined as ship managers and executive authority responsible for structural impacts and operational matters) need to be able to resolve the likelihood and consequence of a risk or choose to gather additional information over a ship's life cycle (Doerry, 2018). The consequence of not meeting this need can be detrimental to a nation's maritime capability. For example, decisions to defer maintenance, based on analysis with poor articulation of uncertainty and incomplete information, led to the early decommissioning and extended unavailability of Royal Australian Navy (RAN) ships (Rizzo, 2011). In addition, in some cases, it may be necessary to maintain a ship such that it reaches a service life beyond the design service life (Hess et al., 2015, Eccles et al., 2010); that is, a ship may undergo a Life of Type Extension (LOTE). Therefore, improved understanding of the benefits and limitations of different fatigue life evaluation approaches would improve the effectiveness of the management of risks related to the LOT of naval ships.

High Speed Light Craft (HSLC) have been increasingly used by navies (Magoga et al., 2017, Tuitman and Hoogendoorn, 2014). This has been partly driven by operational requirements including the surveillance, interception and, if necessary, boarding of commercial vessels to support law enforcement. HSLC are often constructed using welded aluminium alloys or high tensile steel due to their weight-saving potential, but are vulnerable to fatigue cracking (Crupi et al., 2007, Fricke et al., 2002, Tuitman and Hoogendoorn, 2014). This is a hazard as, in addition to the reduction of availability of the ship, cracking can lead to costly repairs and undermining of safety during operations (Vacca et al., 2007, Stambaugh et al., 2014, Garbatov et al., 2018). Further, HSLC can be vulnerable to slamming leading to the exacerbation of fatigue damage (Magoga et al., 2017).

Much of the research on the uncertainty in fatigue life assessment of marine structures is quantitative and, in general, the overarching aim is to improve design and assessment processes. Examples of uncertainty studies include the influence of construction tolerances on the fatigue damage of a welded ship detail (Blagojevic et al., 2002), the sensitivity of the calculated fatigue damage to the discretisation of modelling parameters (Li et al., 2013, Mohammadi et al., 2016), and the assessment of the uncertainties introduced by different fatigue damage calculation procedures (Garbatov and Guedes Soares, 2012). Where quantitative research is results-oriented, qualitative research is focused on the exploration and description of data (Johnson and Christensen, 2014, Tracy, 2013).

This paper presents the first phase of work in a comparative analysis of different fatigue life evaluation approaches for naval HSLC, using a qualitative process. The process allows consideration of the context of structural LOT management (for example, stakeholder constraints). The results of the analysis include the identification and rating of approaches against the key attributes that characterise a fatigue analysis of a welded ship structural detail. The next phase of the study is also described.

The value of the work is that analysts and engineers can obtain, and articulate to decision-makers, a high-level view of the completeness of the fatigue life 'answer' throughout a ship's life cycle. Analysts conduct the fatigue life evaluation as the basis of recommendations for decision-makers.

Although the focus of the present paper is naval HSLC, and is framed within the Australian Defence CLC, the knowledge gained is applicable to other current and future naval ships that use the same fatigue life evaluation approaches.

2. BACKGROUND

In the present paper, there is a greater focus on fatigue life assessment during the in-service phase of a naval ship than the earlier phases of the CLC when the ship is designed (or selected). The reasons for this focus are as follows:

- Fatigue design guidance and standards for the construction of welded structures are available. In comparison, operational and environmental considerations, particularly for naval ships that have evolving mission requirements, require further evaluation in the context of structural fatigue life management (Stambaugh et al., 2014).
- Fatigue life evaluation of an in-service ship is an opportunity to update the assumptions required as input to the design process.
- The naval ship acquirer may not have knowledge of the design data.
- Continuation of ship operation beyond the design service life is becoming more prevalent due to adequate remaining load-carrying capacity (Groden and Collette, 2017, Hess et al., 2015, Eccles et al., 2010, Stambaugh et al., 2014) and delays with commissioning of the new capability.
- The Commonwealth's substantial investment in the Naval Shipbuilding Plan demands Defence delivers value to Government, highlighting the imperativeness of the sustainment phase of the capability life cycle.

Fatigue design can be defined as evaluations conducted during the ship design process to prevent fatigue cracking in structural members. Design characteristics of a welded joint, such as abrupt changes in section and weld stop/starts, can significantly influence the fatigue behaviour of the structural detail. However, these characteristics can be controlled somewhat during design (Kramer et al., 2000) and fatigue design guidance for naval ships as well as welded aluminium structures is available (Sieve et al., 2000, Technical Committee CEN/TC 250, 1999, Hobbacher, 2008, Maddox, 2003, Kramer et al., 2000). Further, the welding execution quality of aluminium alloys can be taken into account, to a degree, by employing detail categories that meet ISO 10042:2005 (International Organization for Standardization, 2005).

The fatigue design process of a ship involves many assumptions and hence potential inaccuracies. Much of the input data required for design is inexact; this can add to the risk associated with any LOT conclusions based on the design (Kramer et al., 2000). Thus, assessment of the fatigue life of an existing structure is an opportunity to improve the accuracy of some of the assumptions (Maddox, 2003). This can improve future ship design and management of the current fleet.

In countries with modest Defence budgets like Australia, the acquisition process of naval ships is often constrained by the adoption of strategies that give preference to Off-the-Shelf designs. The Off-the-Shelf design (the parent design) is modified into what is perceived to be a mature design. Unlike a navy designing a ship to meet a capability gap, the Off-the-Shelf acquirer will not have knowledge of the parent design's requirements and design data (Morris et al., 2018, Schank et al., 2014).

3. METHOD AND ANALYSIS

Much of the research on fatigue life assessment of ships is ultimately about improving the accuracy or reducing the variability of the results. In contrast, the purpose of the current research is to inform selection of the approach used to assess fatigue-related deterioration of naval ships, and limitations and complexities regarding assumptions and uncertainties. To achieve this aim, qualitative research is employed. Qualitative research is exploratory in nature, and aims to build a larger knowledge base about a problem space. Documented findings drive the inquiry. The resources needed to comprehend an idea are seen as interwoven within the context (Tracy, 2013). For example, the design solution for a frigate could take into account the functional requirements as well as the local industrial capabilities (Schank et al., 2014).

To guide the qualitative analysis, the following questions are posed:

- What are the key attributes of a fatigue analysis of a welded ship structural detail?
- To what extent do different fatigue analysis approaches achieve the key attributes?

By posing and answering the above questions the intention is to build a decision-making aid regarding the most appropriate fatigue analysis option in the context of availability of resources, budget, desired precision, and schedule.

The analysis process is illustrated in Figure 2. The process begins with a data review that is framed by the questions above. This step is followed by scrutiny and codification of the collected information, which involves reduction of the information into key 'attributes' that describe the problem under investigation (Leedy and Ormrod, 2001). In the final step, these attributes are used as the basis for comparison between the fatigue analysis approaches using expert judgement.

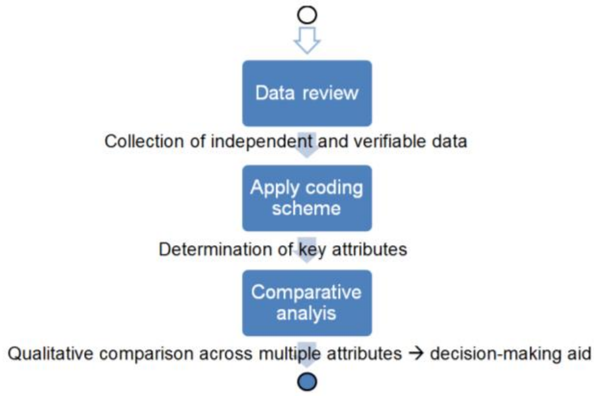

Figure 2: Qualitative analysis process and inputs and outputs at each step

It is sometimes necessary to use expert judgments, or informed opinions based on the experience and knowledge of experts in a particular field, to understand the potential scale of uncertainties and related actions. This is due to the inability of scientific models to fully capture stochastic variations. For instance, asset life-cycle deterioration modelling is challenging because data often only covers a short period of time, while maintenance strategies, technologies, and external circumstances change over time (Ter Berg et al., 2019). Information on uncertainty from experts can be collected in a structured or informal manner (Aspinall and Cooke, 2013, Hifi and Barltrop, 2015, Ter Berg et al., 2019). Use of such disparate methods, from asking an individual expert for their judgement through to following a formalised procedure to aggregate the judgements of several experts, are accepted ways to describe the uncertainty about complex parameters (Colson and Cooke, 2018, Watkins et al., 2012).

In the current stage of the work, the comparative analysis is based the judgement of an individual expert (that is, one expert performs the analysis). The next phase of work is a comparative analysis with elicitation from multiple stakeholders and experts (described further in Section 4).

3.1 FATIGUE ANALYSIS APPROACHES

Most of the fatigue analysis approaches, or 'options', have been identified in a technical review conducted by Magoga et al. (2015). The options are listed in Table 1.

Table 1: Fatigue analysis options

Option	Definition
#1 Rules-based approach (implicit)	With respect to HSLC, the approach of some classification societies is to assume that '… structural fatigue is implicitly and sufficiently accounted for when the connection details, design loads, and fabrication quality are acceptable' (Magoga et al., 2015, pp. 5-6).
#2 Simplified fatigue analysis	Simplified fatigue analysis assumes a stress spectrum at a structural detail, which is defined by the shape and maximum with an appropriate probability level. For example, Germanisher Lloyd's Rules for Classification and Construction – Seagoing Ships (2013) provides a standardised linear and convex spectra as shown in Figure 3. In general, the stresses are calculated using loads defined in design rules.
#3 Spectral Fatigue Analysis (SFA)	In SFA, a ship's lifetime exposure at sea is divided into 'cells' that represent weighted combinations of sea state, ship heading with respect to the waves, and ship speed. Thus, the stochastic response in the cell becomes statistically stationary. The total fatigue damage is the summation of the fatigue damage from each cell.
#4 Rainflow counting + cumulative damage theory (CDT) applied to full-scale stress data	Rainflow counting is a technique to reduce a stress time history into a histogram of stress cycles (Rychlik, 1987). Full-scale stress data can be obtained through the implementation of a hull monitoring system (HMS). CDT calculates the fatigue damage (D) caused by all stress cycles (k) as (Miner, 1945): $$D = \sum_{i=1}^{k} \frac{n_i}{N_i}$$ n_i and N_i are the number of actual cycles experienced and cycles to failure, respectively, for the i^{th} interval.
#5 Analysis of maintenance data	Inspection or hull survey of a ship provides information on the condition of a structure. Maintenance reports are a real-world account of fatigue-related defects.
#6 (#4 + #5)	Option #6 represents a through-life hybrid fatigue assessment framework proposed by Magoga et al. (2019).

Hess et al. (2015, p. 7) argue that 'integrated approaches for future maritime design and operations … factoring in uncertainty, likelihood, reliability, consequence and risk can better inform the owner/operator of the asset's health and provide a route for managing that health efficiently and effectively'. Stakeholder involvement is fundamental to structural LOT management decisions. A stakeholder is a person, group or organisation that has interest or concern in an organisation; stakeholders in ship safety, for example, include the operator, owner, regulator and the public. In this regard, the present study is scoped to the S-N curve concept as described in (Technical Committee CEN/TC 250, 1999). Although fracture mechanics allows detailed fatigue life analysis by taking into account the crack geometry and the load sequence, it requires considerably more effort than the S-N curve concept. In addition, the S-N curve concept is widely accepted in the maritime industry (Du et al., 2015, Hodapp et al., 2013, Maddox, 2003).

In addition, time-domain hydroelastic simulation is not included in Table 1. In principle, this methodology can predict the slamming loads on ships. However, its application for a large number of conditions, as required for fatigue analysis, is impractical due to the long simulation time.

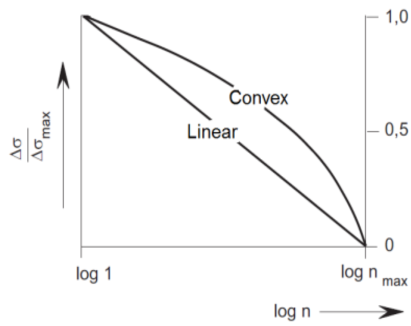

Figure 3: Standard stress range spectra given by Germanischer Lloyd (2013)

3.2 DATA REVIEW AND CODIFICATION

The data review technique comprises examination of a variety of sources to collect independently verifiable information (Watkins et al., 2012). In this study, data review is used to gain a first-order understanding of influences and themes in the literature (the term 'literature' is used hereon to refer to the data being reviewed). The source and search terms for the collection of literature are given in Table 2.

Table 2: Search terms for data collection

	Type/Syntax and Justification
Source	Online publications from academia, industry, and defence organisations • In general, online publications are accessible to all LOT management stakeholders.
Keywords	ship AND fatigue • The data must be relevant to ships and fatigue.
	steel OR aluminium • The majority of ships are constructed from steel and marine-grade aluminium alloys. Also, the limit state of non-metallic structures (that is, composites) varies considerably – it usually depends on the design of the composite lay-up.

	naval OR navy OR "coast guard" OR patrol OR "high speed craft" OR "high speed light craft" • The data must pertain to naval vessels. • Patrol and coast guard boats/ships are sometimes classed under a classification society ruleset for HSLC, or meet the criteria of HSLC/HSC. • In general, classification societies' rules for HSLC cover the High Speed Craft (HSC) code (Organisation, 2000).

Table 3: Identified key attributes of fatigue analysis

#	Key Attribute and Justification
I	Probabilistic framework/ analysis • This attribute is required to understand importance and interaction between various factors to fatigue damage. • It enables the limits of the structural performance to be accurately established. • Fatigue damage in ship structures is highly uncertain. (Dong and Frangopol, 2016, Liu et al., 2019, Yang and Frangopol, 2018, Garbatov and Guedes Soares, 2012, Thompson, 2018, Kwon et al., 2013, Knight et al., 2015, Magoga and Dwyer, 2018)
II	Accounts for slamming • Slamming can have a considerable influence on the fatigue life of HSLC and naval ships when compared to the global wave induced stresses alone. (Thomas et al., 2003, Zhu and Collette, 2011, Drummen et al., 2008, Kwon et al., 2013)
III	Can inform maintenance actions • Fatigue cracking may require maintenance, which can lead to unanticipated costs and loss of availability. (Dong and Frangopol, 2016, Hifi and Barltrop, 2015, Eccles et al., 2010)
IV	Allows assessment of remaining life • This attribute of fatigue analysis could reduce maintenance and life-cycle management costs. • Could increase operational availability of ship. • Will assist if there is a need to extend life of ship. (Groden and Collette, 2017, Diez-Olivan et al., 2019, Hess et al., 2015, Eccles et al., 2010, Doerk, 2017)
V	Practical ('pragmatic') • A major obstacle to implementation of a fatigue analysis approach for marine structures is inefficiency. • Approach should be able to be linked to naval engineering/management systems. • Government ship acquisition directives may emphasise the use of industry practices. • Budgetary constraints exist. (Cui, 2003, Baltrop, 2013, Sielski et al., 2002, Department of Defence, 2017d, Department of Defence, 2017a, Dean et al., 2008)

The collected literature was then codified. Firstly, the data was manually scrutinised for relevance to ship fatigue life assessment. Secondly, topics in the data were clustered by commonality to discern the key attributes (listed in Table 3). An attribute had to appear in at least three sources, which are also cited in Table 3, to be considered far-reaching.

3.3 SCORING OF OPTIONS

The approach to rate the fatigue analysis options against the identified key attributes takes aspects from Comparative Risk Assessment (CRA). CRA offers a systematic framework for evaluating variables that pose different risks in problem-solving (Morgenstern et al., 2000). The analysis of the options is a mix of 'hard' and 'soft' techniques (Watkins et al., 2012) as:

- Soft techniques use individual opinion and are not externally verifiable.
- Hard techniques are externally verifiable because data review is part of the process.

The options are rated using a six-level scale shown in Figure 4. The scale represents the extent that the options exhibit the key attributes, and is assumed to be linear. The attributes are assumed to have equal importance.

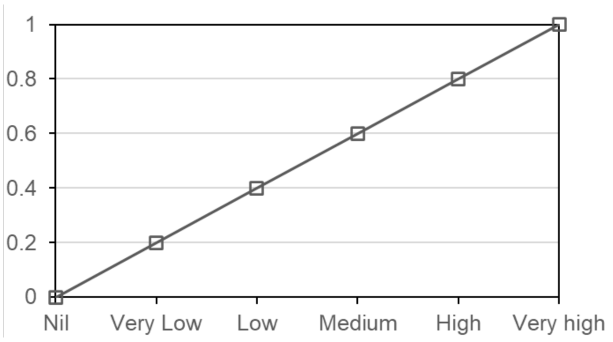

Figure 4: Rating scale, for extent that option achieves an attribute

The ratings are assigned to each option based on the author's experience and accumulated evidence (Magoga et al., submitted for publication, Magoga, 2019, Magoga et al., 2019, Magoga and Dwyer, 2018, Magoga et al., 2017, Magoga, 2017, Magoga et al., 2015, Magoga et al., 2016, Magoga and Morris, 2019). The overall scores of the options are shown in the right outermost column of Table 4.

Table 4: Comparison of extents that different fatigue life analysis options (Table 1) achieve key attributes

Option	Attributes – equally weighted					Sum
	I	II	III	IV	V	
#1	Nil 0	Nil 0	Nil 0	Nil 0	Very high 1.0	1.0
#2	Nil 0	Low* 0.4	Nil 0	Low 0.4	Very high 1.0	1.8
#3	Very high 1.0	Low* 0.4	Low 0.4	Med. 0.6	Med. 0.6	3.0
#4	High 0.8	Very high 1.0	Med. 0.6	High 0.8	Low 0.4	3.6
#5	Low 0.4	Very high 1.0	High 0.8	Low 0.4	High 0.8	3.4
#6	High 0.8	Very high 1.0	High 0.8	High 0.8	Low 0.4	3.8

4. DISCUSSION

Based on the rating scale and equal weighting of the attributes, the highest rated option is #6 (hybrid fatigue assessment framework) followed by #4 (CDT applied to full-scale stress data). The lowest rated option is #1 (rules-based approach).

The scores for Options *#2* and *#3* for attribute **II** (marked with *) are conditional, as follows:

- The judgement that Option *#2* (simplified fatigue analysis) achieves attribute **II** to a low degree depends on the stress distribution assumed. Analysis of the fatigue damage at structural details is heavily dependent on the representation of stress ranges (Magoga et al., 2016).
- The assignment of a low rating for Option *#3* (SFA) in achieving attribute **II** is based on the use of linear hydrodynamic analysis to calculate the external loads on the ship. Typically slamming impacts are neglected (Gao and Moan, 2008, Kim et al., 2002), which may reduce the applicability of SFA for HSLC. More generally, the reliability of the results from SFA depends on how well the operational profile and response are represented (Magoga, 2019).

Option *#1* can be seen as a typical engineering design approach that has a static perspective with well-defined goals and requirements (Ross and Rhodes, 2008). It is considered that Option *#1* (assumption that a ship's design service life will be met if it is designed to a set of classification society rules) does not achieve attributes **I** to **IV** but is highly practical. In general, design to classification society rules provides the minimum standard for ship structural safety. Classification societies arguably take design life variables into account through their experience. This is in part due to the complexities in naval ship design, and difficulties in the estimation of non-linear loads and the failure behaviour of structural items (Collette, 2011). However, it is generally difficult to gain an understanding of how different elements of classification society experience directly link to attributes **I** to **IV**. In general, application of characteristic loads with established analysis procedures and acceptance criteria is satisfactory when the structural life of the ship is not a key design driver. For use in, for example, assessment of the remaining life, loads and acceptance criteria that are explicitly linked to actual failure types and mission capability are needed (Collette, 2011). In addition, treatment of the fatigue life as a static value may not be a suitable means to allow for evolving operational requirements (Ross and Rhodes, 2008), which is a need elicited from the Australian Naval Shipbuilding Plan (Department of Defence, 2017c)

In contrast, Option *#4* (rainflow counting plus CDT applied to long-term stress data) achieves attributes **I** to **IV** to a relatively high degree but is more difficult to implement. Option *#6*, which combines Options *#4* and *#5*, offers achievement of key attributes **I** to **IV** to a greater level than that of the individual options. It has the potential to assure seaworthiness throughout the CLC, by explicitly linking hull monitoring, and maintenance data to seaworthiness management (Magoga and Morris, 2019). However, the resources needed to initialise this option are relatively significant.

For Option *#5* (analysis of maintenance data), a low rating was assigned to attribute **IV**. Option *#5* provides a real-world account of fatigue-related defects, and implicitly takes into account slamming. However, its use is argued to be the 'shortfall of many LOTE studies in the past' (Sanders, 2019). In a similar vein, Rizzo (2011) determined that a lack of good configuration management documentation and inadequate maintenance records were causal factors to failings in the sustainment of Australian Defence maritime capability. The quality of maintenance data must be acceptable to be useful (Hodkiewicz and Tien-Wei Ho 2016, Hifi and Barltrop, 2015).

The labour and monetary costs of the options were not considered in depth within attribute **V** (practical/pragmatic). In addition to understanding operational requirements, it is important to offer a costs-benefits analysis that can be used to decide if a particular approach is worth the investment (Perez et al., 2010, Liu et al., 2019, Magoga and Morris, 2019). For instance, if a naval structure is designed using the 'safe life' philosophy so that it should not fail due to fatigue damage during its service life, why should it be monitored? Using this argument, the cost of choosing Option *#4* is high but for little benefit. However, the key assumptions that underlie this argument (for example, the ship is used in the same manner as that stipulated during the Risk Mitigation & Requirements Setting phase of the CLC) can change or be untrue. For the adoption of an approach to fatigue life management to be justified, the sum of both the tangible and intangible costs needs to be low relative to the benefits (Perez et al., 2010). Intangible costs include those arising from project planning, training personnel, maintenance and repair, and disposal.

The suitability of a fatigue analysis option is also dependant on the availability of the required input data during the different phases of a ship's CLC (Magoga et al., 2015). For example, in the absence of detailed long-term distributions of stress ranges, many classification societies assume a distribution (for example, refer to Figure 3). If the classification society or owner desires a greater level of confidence in the estimated fatigue life, a simplified fatigue assessment may be performed. These options may be appropriate for displacement ships and during the Acquisition phase of the CLC. However, the applicability of simplified fatigue life for HSLC is inconclusive (Magoga et al., 2016). In contrast, SFA could be utilised as it allows probabilistic rather than deterministic analysis. However, the analyst needs to be mindful that the fatigue life 'answer' is based on the given speed profile, heading distribution, and operational area (wave scatter diagram). As demonstrated by Magoga and Dwyer (2018), the calculated fatigue life values based on an indicative design speed profile and the actual in-service speed profile of an 56 m aluminium patrol boat differed substantially.

Bias influences the scoring of the options in Table 4. The type of bias is 'a systematic discrepancy between the "correct" answer in a judgmental task … and the expert's actual answer to such a task' (Montibeller and von Winterfeldt, 2015p. 1231). For example, it was the experience of the author that the installation and custodianship of a HMS implemented on a RAN ship (Magoga, 2017) was resource intensive. This experience sways the ratings for Options *#4* and *#6* against attribute **V**. However, others have recognised the need to determine cost-efficient HMS plans (Sabatino and Frangopol, 2017, Koboević et al., 2018). Thus, the author's judgement is consistent with external information. There are various means to correct single expert bias, such as group elicitation techniques. However, correction of any bias must be carefully implemented to avoid introduction of other issues. For example, within a group there can be disparate motivations to providing accurate judgements (Montibeller and von Winterfeldt, 2015).

4.1 WHERE TO NEXT?

The next phase of the work is to engage numerous experts and stakeholders in a CRA. The stakeholders will include Navy, Government, academia, classification societies, and ship designers and constructors. Within each of these stakeholder groups will be subject matter experts. The main goal of a formal elicitation of expert judgement is to remove as much subjectivity from decision-making as possible, by incorporating meaningful scientific judgement based on specialist knowledge, practised reasoning skills and real experience (Aspinall and Cooke, 2013).

This analysis would differ to that given in Table 4, as each respondent would be asked to weigh the importance of the key attributes. Each option is bound by stakeholder constraints of cost, schedule, and risk appetite (Dawson et al., 2012, Dong et al., 2016). Attitudes towards the key attributes of a fatigue analysis will also differ amongst stakeholders and experts. These factors will be taken into account in the next phase of the work.

5. CONCLUSION

An evidence-based decision-making aid for fatigue life analysis of naval HSLC, focus on fatigue life assessment during the in-service phase of the life cycle, is proposed. The first phase of this development is reported.

This work has been motivated by the need for improved understanding of the benefits and limitations of different fatigue life evaluation approaches, to in turn improve the effectiveness of the management of risks related to the structural Life of Type (and possible life extension) of naval ships.

A qualitative process was employed, which included a data review framed by guiding questions, codification of the collected information, and reduction of the information into key themes or 'attributes'. The attributes formed the basis of comparison between the fatigue analysis approaches – or 'options'. In a preliminary assessment, the options were scored by the extent that they can achieve the different attributes by an individual expert. Assuming equal weighting of the attributes the highest rated fatigue analysis option was a hybrid fatigue assessment framework followed by CDT applied to full-scale stress measurements. The lowest rated option is use of a rules-based approach.

The next phase of the work is to engage several experts and stakeholders in the comparative analysis.

6. ACKNOWLEDGEMENTS

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