BETTER SHIPS, BLUE OCEANS

FReady JIP

A fleet ready combination of physical and virtual hull structure monitoring

Proposal No. 33306

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1 BACKGROUND

In 2007, the USCG and MARIN launched the first of a sequence of joint industry projects working on approaches applicable to service life maintenance and sustainment efforts of US Coast Guard cutters. It turned out that this was the start of one and a half decade of enthusiastic joint research with a large amount of leading partners in the maritime industry, see Figure 1.

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Figure 1: Overview of participants in the Valid JIPs.

The initial Valid JIP was conducted between 2007 and 2013 and delivered:

- Improved simulation tools for ship design thanks to
  - Advanced model tests
  - Validation of a number of simulation tools
  - Understanding of the uncertainties associated with ship design
- More rational structural maintenance decisions thanks to
  - Installation of an extensive hull structure monitoring system on board USCGC BERTHOLF, Figure 2
  - Monitoring and subsequent data analysis

Figure 2: Picture of USCGC BERTHOLF.

For detailed information about the achievements within the Valid project reference is made to the papers presented at the Ship Structure Committee Ship Structures Symposium 2014. Lessons learned from the first phase of the project were used between 2014 and 2018 as part of the second phase of the project the further optimize the hull structure monitoring system and the analysis of the data. The Valid 2 JIP has delivered:

- Approaches applicable to service life maintenance and sustainment efforts thanks to
    - An optimized cost-effective physical hull structure monitoring system design based on the simulation model and global deformation modes installed on board USCGC STRATTON, Figure 3
    - Development and implementation of new near real time wave estimation methods based on motion measurements (ship as wave buoy)
    - Continued monitoring and evaluation of measured data in reliability framework
- First steps toward a virtual HSM system thanks to
    - Investigation of usefulness of hindcast wave databases

Figure 3: Picture of USCGC STRATTON.

The achievements reached within the Valid 2 JIP were presented in four papers at the ASNE TSS 2019 conference. In the first two Valid project monitoring was largely done with accurate sensors and a fully synchronized measurement system on board. With the knowledge gained here and benefitting from developed technologies, further improvements in the cost, benefit area were envisioned and investigated within the third Valid JIP. The Valid 3 JIP will finish early March 2022. The project has delivered:

- Physical approaches applicable to service life maintenance and sustainment efforts thanks to
    - Continued data analysis and condensing this to essential structural integrity key performance indicators
    - Improved ship as a wave buoy approach using machine learning
    - Risk assessment of ship under different maintenance and operating scenarios
- Virtual approach for service life maintenance and sustainment efforts thanks to
    - Investigation of accuracy of hindcast wave data in the light of virtual hull structure monitoring (VHSM)
    - Investigation into the accuracy of VHSM itself

Together with the USCG, MARIN is now launching the FReady JIP, aimed at developing a fleet ready combination of physical and virtual hull structure monitoring. The goal of the project is further described in Section 2. Section 0 presents the scope of work. The benefits and deliverables of the project are described in Section 4 and 5, respectively.

2 FREADY JIP GOALS

The main goal of the FReady JIP is *fleet deployment optimization and structural integrity management through an efficient, low-cost combination of virtual and physical monitoring*. Supporting goals of the project are:

- Continued hull structural data analysis for quantifying uncertainties in ship design and operation
- Maturing of the low cost, low intrusive virtual monitoring approach
- Improvement of the strength and resistance assessment for sharper designs and maintenance decisions

3 FREADY JIP SCOPE OF WORK

3.1 General

The scope of work necessary to achieve the goal mentioned in the previous section is visualized in Figure 4. The concept of fleet virtual hull structure (F-VHSM) monitoring should be further developed. At the basis of virtual monitoring are the waves encountered by the ship. Within the project two ways of inferring this input will be investigated, wave hindcast data and ship as a wave buoy (SAWB) approaches. Physical hull structure monitoring (HSM) will provide information about actual environmental and operational conditions as well as corrections that can be applied to the typically linear VHSM approach. The data obtained from the (virtual) hull structure monitoring systems needs to be forecasted. This is the case for both the extreme and the fatigue loads. Finally, up to now, the focus of the Valid JIPs has mainly been on the loading side of fatigue. In this project, also the strength and fatigue resistance will be addressed in more detail.

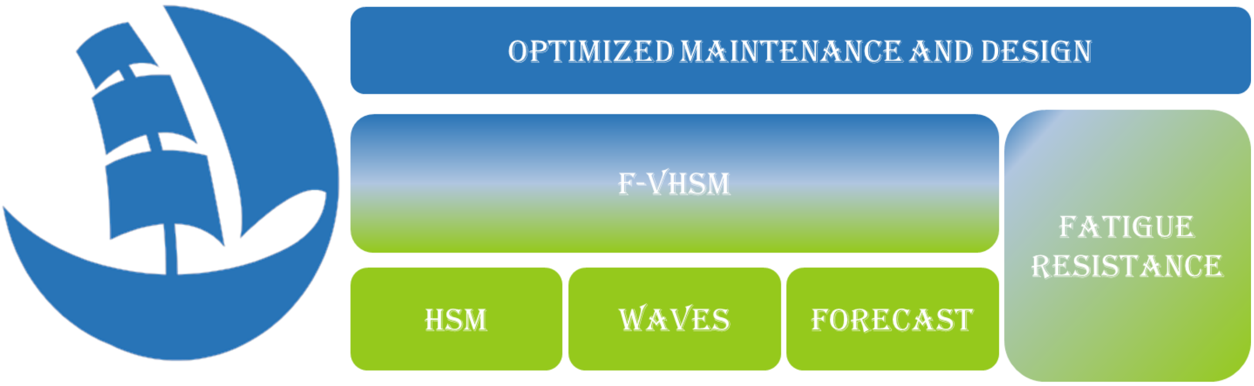

Figure 4: Visualization of the scope of work

3.2 Hull structure monitoring (HSM)

Within this task, the hull structure monitoring of USCGC BERTHOLF and STRATTON and subsequent data analysis will be continued. MARIN will visit both ships and collect the HSM measured data once per year. As part of the Valid JIPs both ships were instrumented with a physical hull structure monitoring (HSM) system that measures:

- Global strains at the midbody section using three long base strain gauges (LBSG), see Figure 5
- Local strains at two selected fatigue sensitive locations in the midship area using unidirectional strain gauges
- Local strains at one selected location in the foreship area using three strain gauges in a rosette configuration
- Motions in the six degrees of freedom of the ship using a motion response unit (MRU)
- Heading and speed of the ship using GPS

The strain data measured at the fatigue sensitive locations are used to monitor the cumulative fatigue loading at these locations with extrapolation to the hotspots. From the strain data measured with the long base strain gauges, the hull sectional loads are derived. Further work on and validation of the conversion matrix approach translating global strains to sections loads will be done. The relevant wave data will be inferred from ship as a wave buoy approaches as well as wave hind cast data, see Section 3.3.

Figure 5: Pictures of long base strain gauges on board USCGC STRATTON

The data obtained will serve two sub-goals. On the one hand the physical hull structure monitoring will provide additional information about the actual environmental and operational conditions. On the other hand, it will also provide corrections to the (nonlinear) response analysis that can be applied to the linear VHSM approach. As an example of results obtained from USCGC STRATTON so far, it was derived that on average the ship has spent 135 days per year at sea, which is less than the 170 days that were assumed during design. It was furthermore found that encountered wave heights are significantly lower than initially assumed in design, see Figure 6. This directly implies the life time of the ship is longer than for which the vessel was designed.

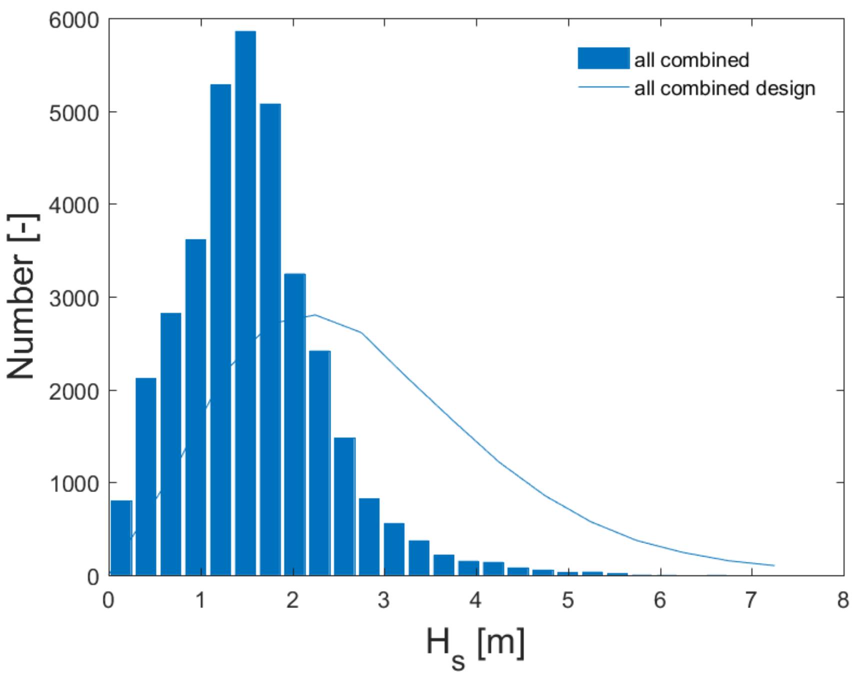

Figure 6: Histogram of the measured significant wave height and assumed during design in the continuous line for USCGC STRATTON

Within the current project a sensor fusion techniques based on data science for optimizing sensor placement will be implemented. The layout of the sensors on board USCGC BERTHOLF and STRATTON is currently determined based on experience with a heavily instrumented ship in combination with analysis methods. Using data science provides a different view on optimizing the sensor layout.

3.3 Wave inference

3.3.1 General

Information about the wave environment encountered by the ship is essential for analysis of the service life maintenance and sustainment efforts. A wave radar is a direct measurement that provides information about the three-dimensional spectrum of the encountered waves. It is, however, an important cost driver in a monitoring system and produces undesired radar signature on military ships. Alternatively, the wave data can be inferred from other sources, like the ship motions or the hindcast databases. The goal of this part of the work is to determine the accuracy of the inferred sea states determined in absence of direct measurements.

3.3.2 Wave hindcast data

Wave hindcast databases are an essential and valuable source of data when it comes to (virtual) monitoring. Work has already been done to investigate the accuracy of the different available databases. There is, however, no simple answer to this question as this depends on the location of the ship as well as the wave conditions itself. In addition, there will also be a difference in the implied accuracy when predicting fatigue or extreme load effects. As part of this task there will be a continued effort of identifying the accuracy of the Copernicus, WaveWatch3 and ERA5 wave hindcast databases in the light of fatigue and extreme load effects.

3.3.3 Ship as a wave buoy (SAWB)

Significant steps have been made in the translation from measured ship motions to information about the encountered waves. Within this project, the step will be made to obtain the wave spectrum (Figure 7) based on measurements and simulations using deep learning technology. This work will be combined with the more traditional ship as a wave buoy approaches that are based on obtaining wave height based on the measured ship motions and calculated motion RAOs. Further improvements of the SAWB estimates will be done

- using correction factors established based on comparison with ERA5 (or similar), and
- using strain gauge data in addition to or instead of motion data.

For the latter a sensitivity study of strain gauge data versus motion measurements will be done. A further question that will be answered is what uncertainty is introduced by assuming standard spectral formulations for wave spectra compared to using the ground truth (ERA5, WaveWatch, ...) when estimating fatigue.

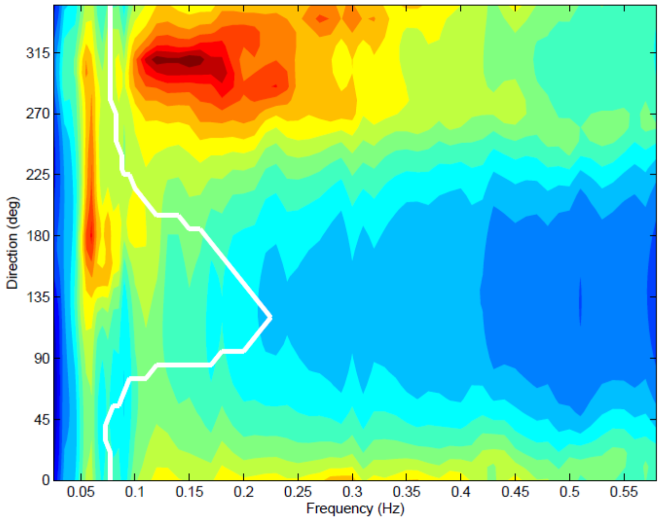

Figure 7: Example of a directional wave spectrum

3.4 Forecasting

The goal of this task is to develop forecasting techniques able to support fleet deployment optimization and structural integrity management. Efforts will be aimed at both fatigue and extreme loads. Forecasting will be done based on data obtained from HSM and VHSM systems. The forecast will be provided with an uncertainty band, which will inherently be larger for the forecast based on VHSM data than HSM data.

An important question to be addressed is how long monitoring is necessary for the purpose of forecasting. After 30 years of monitoring a full operational and loading history of the vessel will be obtained. On the other hand, after only monitoring for one year uncertainties will be quite large. Somewhere in between there is a point where additional monitoring will be of little added value to the forecasted parameter. Here it should be noted that this duration would depend on the parameter under investigation. For instance, the average number of days at sea will converge earlier than the extreme bending moment amidships. These questions will be addressed as part of the current project.

Figure 8 shows the probability of Failure (PoF) of a critical structural detail subject to fatigue accumulation. The figure indicates the reliability of this detail over time in different operational scenarios. This will be taken to fleet level reliability where a combination of HSM and VHSM is used for monitoring of fleet and do forecasts of relevant parameters. This will include updated reliability following deployments and an assessment of reliability after maintenance and lifetime extension programs.

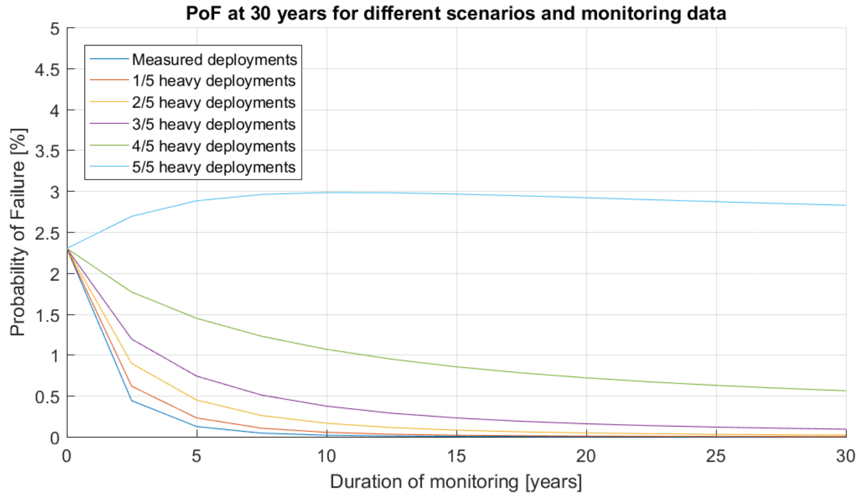

Figure 8: Probability of failure (PoF) of a ship as a function of time and deployments when subjected to fatigue loading

3.5 Fleet virtual hull structure monitoring (F-VHSM)

The objective of this task is to develop the fleet virtual hull monitoring as a low cost, low intrusive monitoring alternative to the current physical monitoring. Significant work on VHSM has been done within the Valid 3 JIP. As part of this task a large part of the NSC fleet will be analyzed in a virtual manner. The data obtained from USCGC BERTHOLF and STRATTON, that are monitored physically, provide insight into realistic operating conditions. It will also provide tool accuracy factors and correction factors for strong (Figure 9) and weak nonlinear loads. The latest procedures developed within the CRS project EVaP will be incorporated into the analysis at the end of the project. In the end, monitoring the entire fleet will provide the option of vessel ranking (Figure 10).

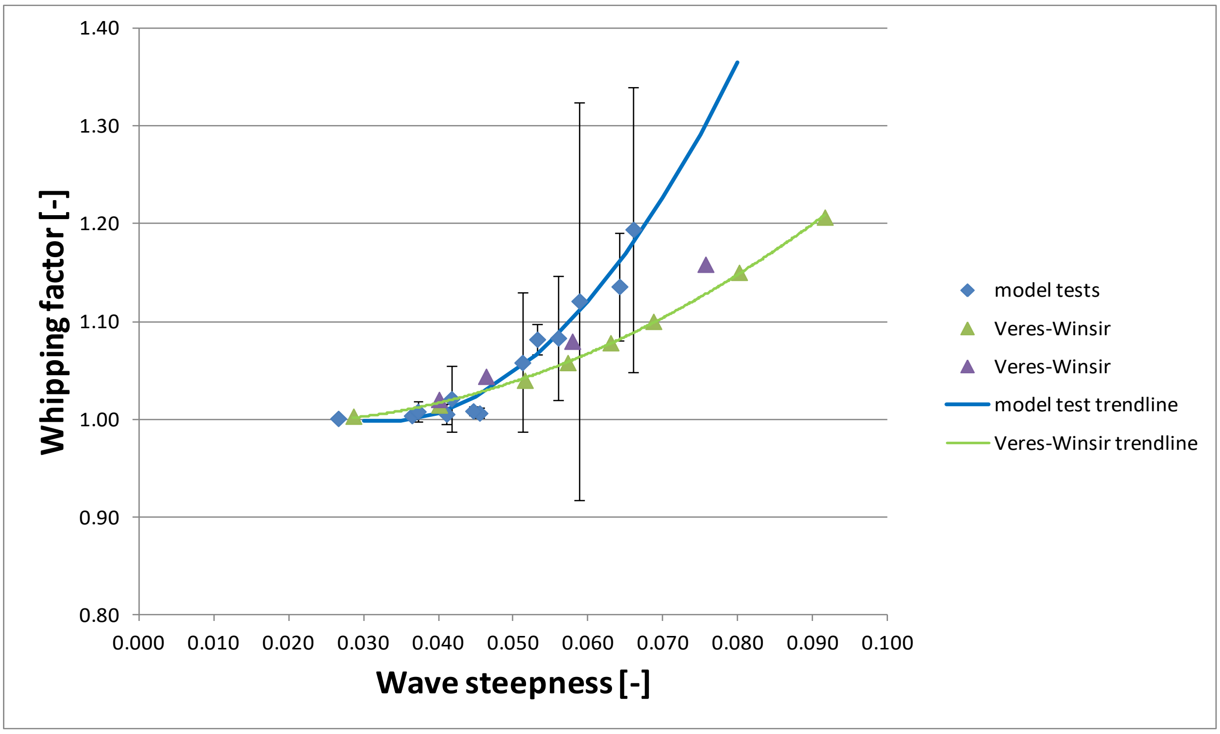

Figure 9: Whipping factor on fatigue damage as a function of the wave steepness for a forward speed of 15kn

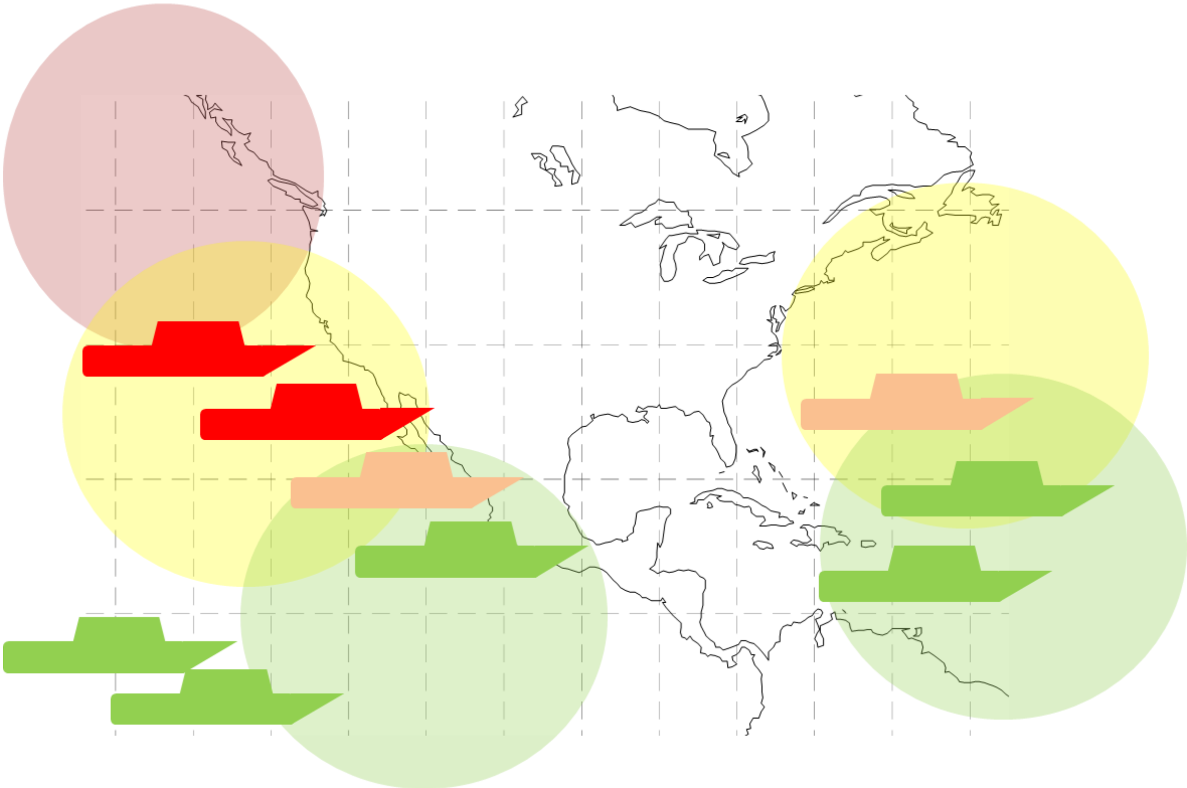

Figure 10: Illustration of vessel ranking for the entire NSC fleet

3.6 Fatigue resistance and damage accumulation

The capacity of the ship’s structure to withstand fatigue loading is an essential part in the calculation of the fatigue life of a ship. Normally, the fatigue load capacity is calculated based on an appropriate fatigue class for the most vulnerable structural details. More methods that are sophisticated require the designer to use finite element models to calculate the local stress state, using for example the hot spot stress approach or stress concentration factors. Resulting stress histories are used in combination with the appropriate SN curves.

The variation in underlying data of SN curves (Figure 11) and the need to avoid premature failure of structural details are the reason why large margins are inherently included. For design purposes, such margin may be acceptable; however, during operation, these margins are making condition based maintenance difficult. For example, when an advisory system indicates risk of finding a failure, based on onboard monitoring and the available structural capacity limits, there is 2.5% probability of finding a failure. No crew or owner will find this an acceptable criterion.

The aim of this task is to improve the reliability of such warning systems. Bayesian Believe Network will be used to cover the fatigue load capacity. Expected values for fatigue strength, actual stress ranges at the hot spot and external effects such as loading condition and workmanship are included. Updates of these values are enabled by monitoring data, inspection data and improved description of the structural capacity. Mean values and their corresponding variation are explicitly included in the fatigue strength assessment.

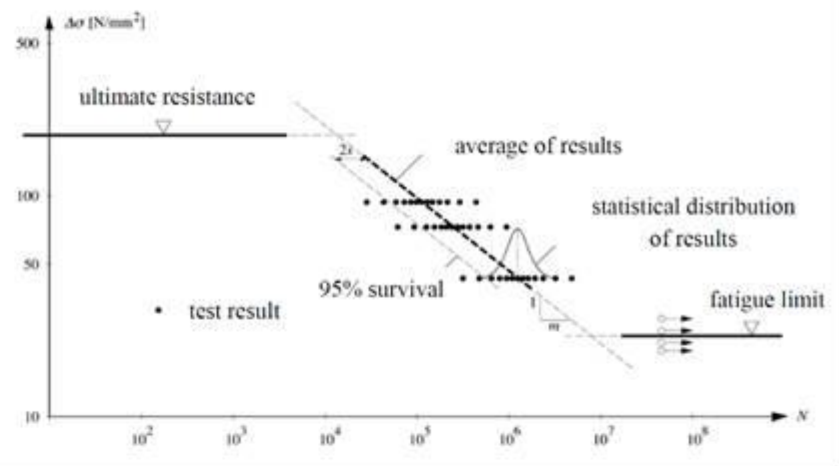

Figure 11: Example SN curve relating stresses to number of cycles to failure[1]

The theoretical fatigue capacity according available standards will be compared to direct calculation methods such as the hot spot stress approach and total stress concept. Such direct calculation methods enable to address more local input parameters and include sensitivity to certain loading and geometry effects. Two structural details are selected to perform experimental validation. Both details are subjected to fatigue testing, supplementing already available experimental data from these structural details. This will contribute to an improved understanding of the actual allowable margins in fatigue capacity.

Finally, the fatigue load bearing capacity calculation is further enhanced by taking into account details about the stress history. Large waves, launching and still water loads influence the fatigue crack growth behavior. Therefore, load effects are quantified and methods are provided to incorporate the load effects in the fatigue lifetime assessment.

3.7 Optimized maintenance and design

The knowledge developed in this and the previous projects will be applied to reduce the costs of fleet deployment optimization and structural integrity management. The basis is that a good tradeoff between accuracy and costs can be found with only a small number of ships monitored with HSM and the rest virtually. A question to be answered then becomes: How does this accuracy change with number of ships monitored physically and virtually?

Figure 12 shows the accuracy of fleet monitoring as a function of the number of ships installed with an HSM system. Here it should be considered that monitoring with an HSM system is more accurate than with a VHSM system. If the entire fleet has an HSM system on board the overall fleet accuracy will be that of the HSM system. Similarly is the entire fleet is monitored virtually. Between these two extremes the accuracy changes, where the accuracy increases with the number of HSM systems. With that increase also the costs increase. Somewhere there is an optimum.

[1] Nussbaumer et al., Fatigue Design of Steel and Composite Structures, Eurocode 3: Design of Steel Structures Part 1-9 - Fatigue/Eurocode 4: Design of Composite Steel and Concrete Structures, 2018, DOI:10.1002/9783433608791

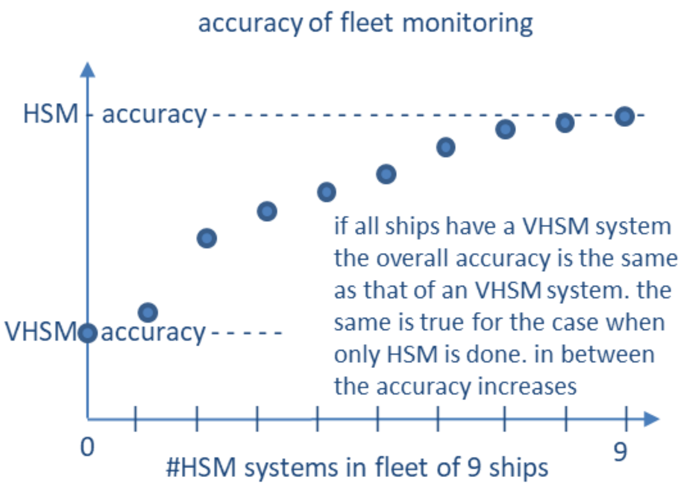

Figure 12: Accuracy of fleet monitoring as a function of the number of ships installed with an HSM system.

4 FREADY JIP BENEFITS

Below is an overview of the benefits of the FReady project for different participant roles.

For operators

- Low costs structural integrity monitoring
- Fleet monitoring scheme using combined physical and virtual monitoring
- Rational data for maintenance and life time extension decisions at optimized costs
- The developed approach will be applied to the NSCs but can be applied to any fleet of ships

For class societies

- Input on how monitoring results can improve ship design and decisions on maintenance and life time extension
- Insight in uncertainties governing the structural design of ships

For ship builders

- Input to support better future ship designs
- Support for more economic and on-demand ship maintenance support options

5 DELIVERABLES

The deliverables for the project are the following.

1. Presentations of deployments and combined deployments of USCGC BERHOLF and USCGC STRATTON
2. Report with improved and validated conversion matrix approach
3. Report with performance of the selected sea state inference technologies
4. Report with forecasting techniques able to support fleet deployment optimization and structural integrity management

5. Report outlining an approach for fleet virtual hull monitoring as a low cost, low intrusive monitoring alternative to the current physical monitoring
6. Report with an improve understanding and approach for obtaining the fatigue load bearing capacity
7. Report with an optimal monitoring strategy
8. The main deliverable of the project will be a report summarizing the results from the work carried out within the joint industry project

6 SCHEDULE AND PARTICIPATION FEE

The project will start on the first of April 2022. The project will last for three years and end on 31 March 2025. The kick-off meeting is scheduled for Q2 2022. There will be two progress meetings per year. Virtual attendance will be facilitated.

7 COSTS

	kEuro
Hull structure monitoring	220
Basic analysis of USCGC BERTHOLF and STRATTON data	*60*
Extended analyse of USCGC BERTHOLF and STRATTON data	*60*
Improved conversion matrix approach	*60*
FUSION sensor layout	*40*
Wave inference	75
Wave hindcast	*25*
Ship as a wave buoy approach	*50*
Forecasting	140
Forecasting fatigue	*30*
Forecasting extremes	*30*
How long and what to monitor?	*20*
Fleet level reliability	*60*
Fleet virtual hull structure monitoring	125
VHSM on all NSCs	*100*
Correction factors	*25*
Fatigue resistance and damage accumulation	360
Bayesian networks for fatigue resistance	*90*
Fatigue assessment non-standard details	*195*
Load variation effects	*75*
Optimized maintenance and design	70
Investigation of accuracy	*30*
Cost considerations	*20*
Benefits for design	*10*
Benefits for maintenance	10
Management	50
Total in Euro's	**1040**

The fee for participating in the FReady JIP is 60keuro for the duration of three years (i.e. 20 keuro per year).

Contractual matters are included in the project participant agreement.

8 CONTACT

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