Ship Hull Monitoring System Applied as a Real Time Decision Support System on Fast Ferries

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ABSTRACT

Three new fast catamaran ferries, built from Carbon Fibre Reinforced Polymer (CFRP), have recently been put into service in Norway on the routes Sandnessjøen –Svolvær, and the "Helgelandspendelen" fast ferry services. The waters along these routes can offer severe sea states, sometimes exceeding the wave heights for which the ferries are certified.

The class certificate provides a speed versus significant wave hight limit curve, relying on visual observations of the wave environment by the operator. However, the assessment of the prevailing sea conditions by visual observations will give inaccurate results, and hence a risk for overloading the vessel. As a tool for making sure that the new ferries are operated within their design operating limits, the vessels have been equipped with a ship hull monitoring system (SHMS).

This paper will give an overview of the system setup, methodology, applicability, graphical user interface and results from a high-speed ferry. Other possible applications are also discussed.

1.0 INTRODUCTION

Ship Hull Monitoring systems (SHMS) have been in practical use for the optimal operation and structural lifecycle management of military and civilian vessels from the early 2000's. Fiber optic Bragg grating [1] sensors [2] were recognized as a promising strain sensor technology for use in harsh environments and have since gained wide use in the maritime sector and elsewhere. In the mid 1990's, the Norwegian Defence Research Establishment (FFI) cooperated with the US Naval Research Labs to instrument the Royal Norwegian Navy's (RNoN) mine countermeasure vessel KNM Hinnøy [3]. This work was continued during extensive sea trials on the Royal Norwegian Navy corvette KNM Skjold [4], [5] from 1999, where a method for measuring the global loads from a network of fibre optic sensors was first applied [6]. Since then, SHM systems have been installed on several hundred vessels addressing global loads, fatigue, sloshing, slamming, ice operation loads, passenger comfort and related issues [7].

This early research led to fleet installation on the Royal Norwegian Navy composite vessels. SHM systems were installed on the KNM Skjold class of corvettes, using the system primarily for decision support in adverse weather conditions [8]. The Oksøy and Alta class mine countermeasure vessels were instrumented in the mid 2010's, where operational decisions were guided using data driven models to predict and avoid overloading events [9]. These systems are in continuous use, providing guidance towards the optimal operation of these vessels as well as logging data for further refinement of the response models.

Access to data and results from Navy SHM systems is often restricted. This paper reports on the use of a similar SHM system aiding the operation of a fast catamaran ferry service in the coastal areas of Northern Norway. For these vessels, the vessels' class certificate provides a speed versus significant wave hight limit curve, relying on visual observations of the wave environment by the operator. However, the subjective assessment of the prevailing sea conditions by visual observations may give inaccurate results, and hence a risk for overloading the vessel. The vessels were equipped with SHM systems to ensure that the new ferries are operated within their design limits. The data collected provides a basis for proposing new, optimal sailing restrictions that, if recognized, will enable a better regularity of service as well as improved passenger safety and comfort.

Acknowledgement is made to Boreal and Br AA for providing access to the data.

2.0 HULL STRESS MONITORING CONCEPT

2.1 System Setup and Instrumentation

The SHM system consists of a network of fibre optic strain sensors, an accelerometer, and a radar for measuring the distance between the wet deck and the ocean surface. Further, the system is connected to the GPS onboard, for logging of speed and position data along with data from the sensors.

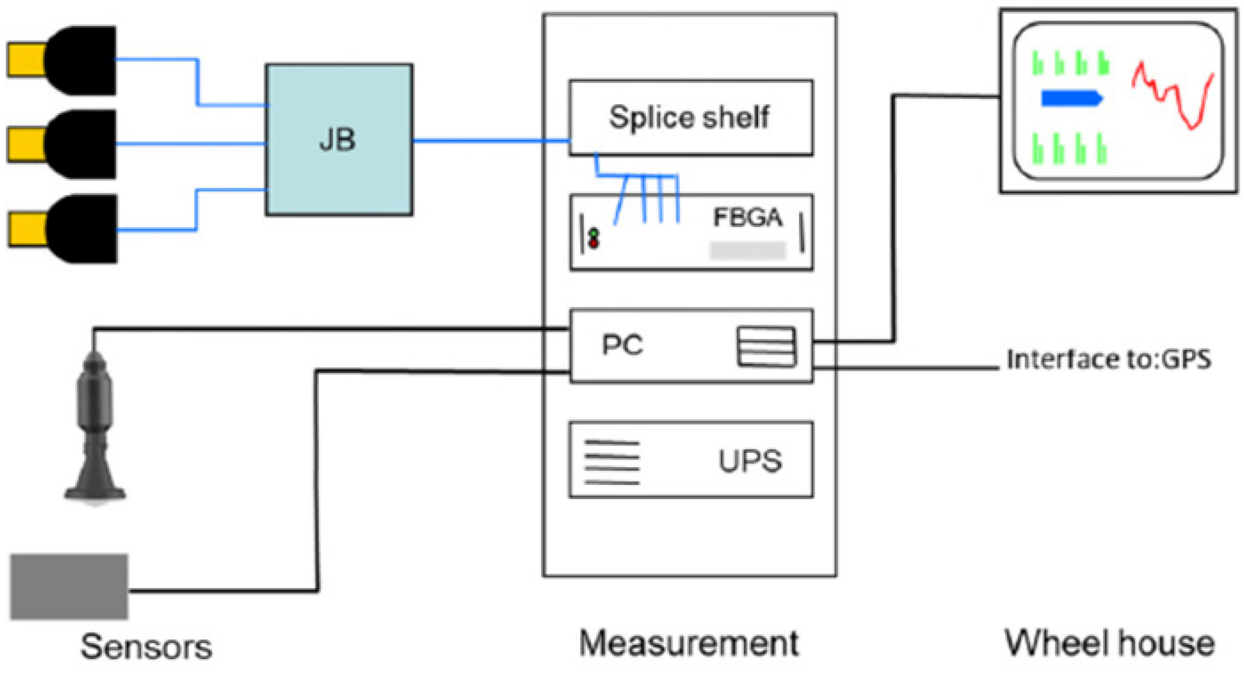

Figure 1: Main components of the SHMS system.

The fibre optic strain sensors are fitted to the hull in the midship's cross-section to monitor the stresses that are representative for the global loads, by which we mean the forces and moments that affect the major loadbearing structures of the hull. The midship cross-section is instrumented by eight strain sensor packages at eight different locations. In addition, one temperature sensor is included at each location for temperature compensation.

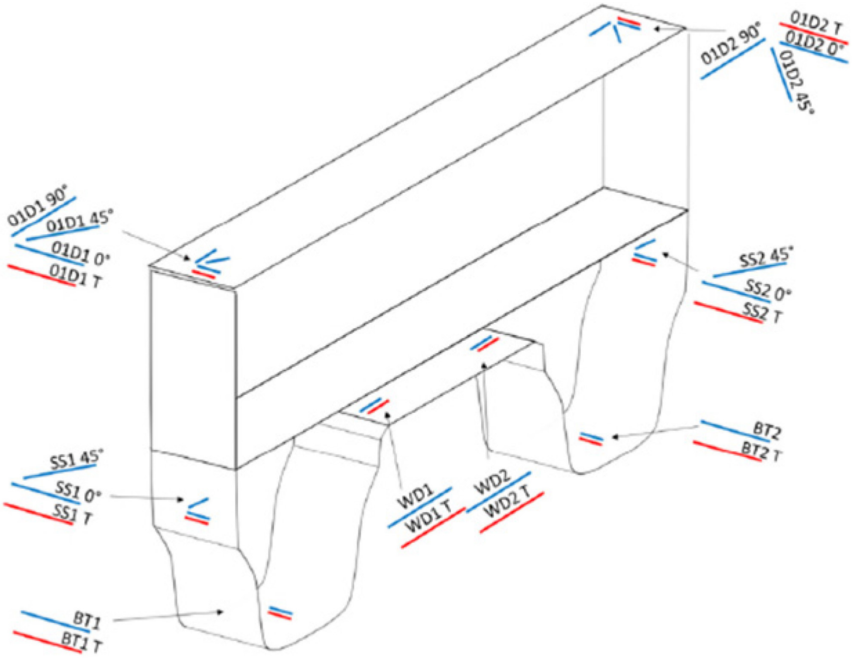

Figure 2: Instrumentation for hull stress and global loads in the midship cross-section.

The individual measurements are combined to find the combined impact of buoyancy, inertia, and waves, to a set of global forces and moments:

- Axial force
- Vertical shear force
- Horizontal shear force
- Vertical bending moment (VBM)
- Horizontal bending moment (HBM)
- Torsional moment
- Transverse bending moment

To find the global forces and moments, a finite element analysis is performed on a Finite Element (FE) model representing the complete hull structure i.e., an as-designed digital twin representation of the hull, to establish a response matrix that connect the strains at the sensor position to the corresponding loads.

The response matrix is calculated by applying a set of unit load cases to the hull structure and retrieving the strains at the indicated sensor positions for each load. As an example, a unit vertical bending moment (VBM) of 1MNm is applied to the FE-model and analysed in the FE-solver. Corresponding strain values are then collected from the result-file at the locations corresponding to the position of the sensors on the real hull.

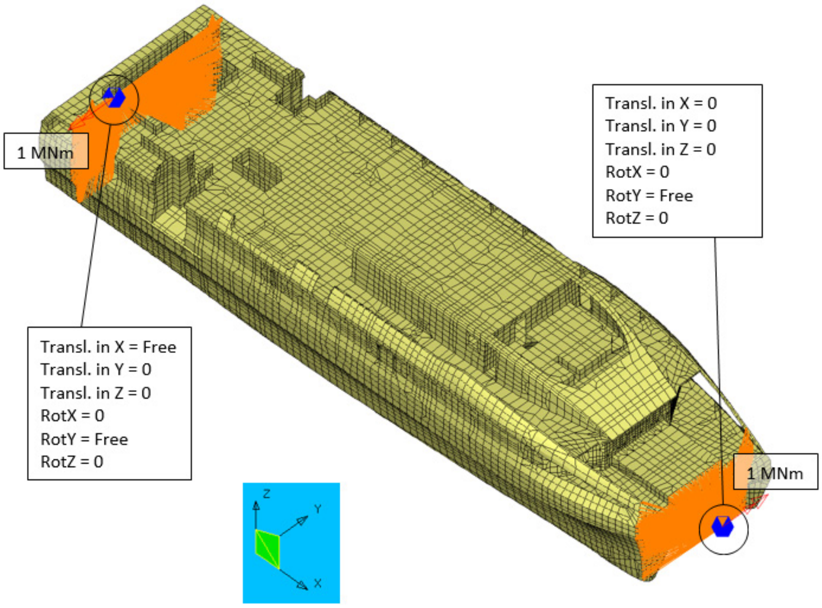

Figure 3: FE-model with applied boundary conditions and unit moment of 1MNm.

By conducting such analyses for all global forces and moments, a response matrix can be assembled. When applied on the real vessel, strains are measured, and the corresponding loads are calculated based on this response matrix.

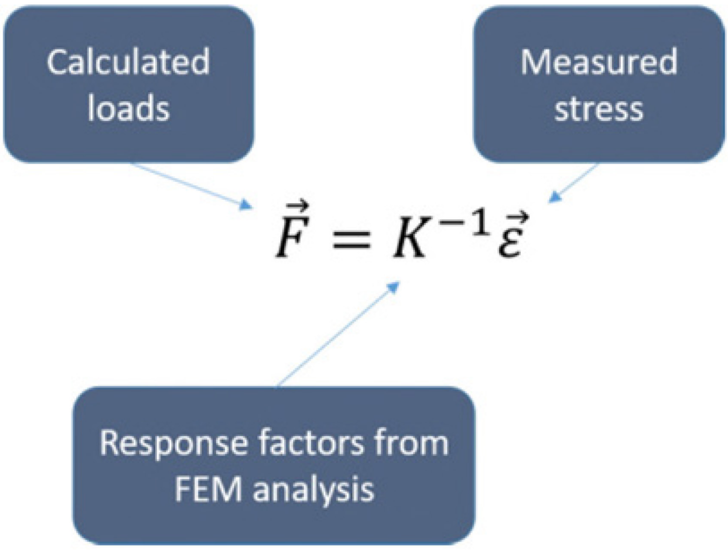

Figure 4: Forces and moments are found form a vector of measured strains and a matrix with response factors from structural analysis.

In addition to the sensor array amidships, three fibre optic strain sensors were fitted to the wet-deck panels in the forward part of the vessel to detect slamming events. For these sensors, the panel loads are deducted directly, based on the strain value measured by the sensors.

2.2 Other Sensors

In addition to GPS for speed, position, and course, the SHM system uses a tri-axis electrical accelerometer for hull acceleration monitoring. The accelerometer is mounted near the ship's centre of gravity (CoG):

- To measure the vertical acceleration at CoG to compare with the design acceleration level (limit)
- To compare measured horizontal acceleration level with limit values for passenger safety as required by the International Code of Safety for High-Speed Craft

Also, the SHMS uses a Vegapulse Radar to measure the gap between wet deck and sea surface during operation. The measurement of the wave profile is added as a function to warn the crew if the air gap between the wet deck and the sea surface is getting alarmingly low. This may be the case in heavy seas with excessive pitch motion. This measurement may also indicate which sea states the vessels have been subjected to.

2.3 Application

The SHMS system on the three vessels were specifically developed as a tool for real time decision support to the operators while enroute. The system offers real time monitoring and statistics of global structural loads, accelerations, slamming events and relative wave profile. The output from the system is presented in a user-friendly graphical user interface (GUI). In addition, the complete load history is stored on a hard drive, enabling further post processing and analysis for planning of actions as necessary, e.g., route optimization or hull inspections for early detection of possible cracks if overloading has occurred.

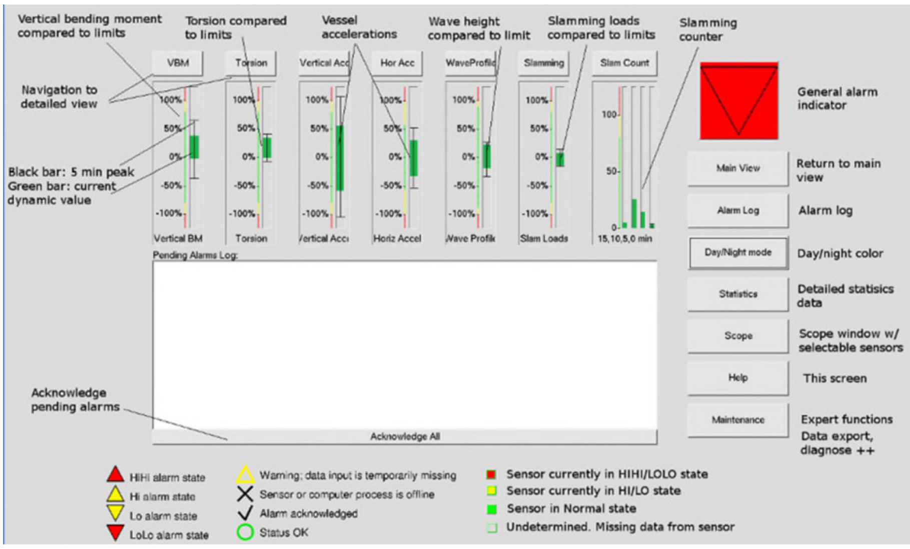

Figure 5: Description of the main components in the graphical user interface.

3.0 RESULTS

3.1 Static Calibration Tests

To validate the response matrix, a validation/calibration test is necessary. Such a test is also required by DNV (DNV-RU-SHIP Pt.6 Ch.9 Sec.3). It is considered sufficient to validate the measurement of Vertical Bending Moment (VBM) only, as this by all practical means also validates the correct setup of the strain sensor array from which all global hull loads are derived. This consideration is in line with the DNV rules:

> **4.2.2 Calibration**
> The global strain sensors in deck measuring stress from the vertical bending moment shall be initially calibrated against the stress from the vertical bending moment of a known loading condition calculated by the loading computer.

Figure 6: Excerpt from the DNV rules.

The test is carried out by applying a known deck load on the vessel while the vessel is at rest in harbour with calm conditions and stable temperature. This deck load changes the vertical bending moment of the vessel. By knowing the exact size and position of the deck load, including the floating position of the vessel with and without the load, the analytical result of the VBM can be calculated. The test results need to be within 5% from the analytical results to be considered acceptable.

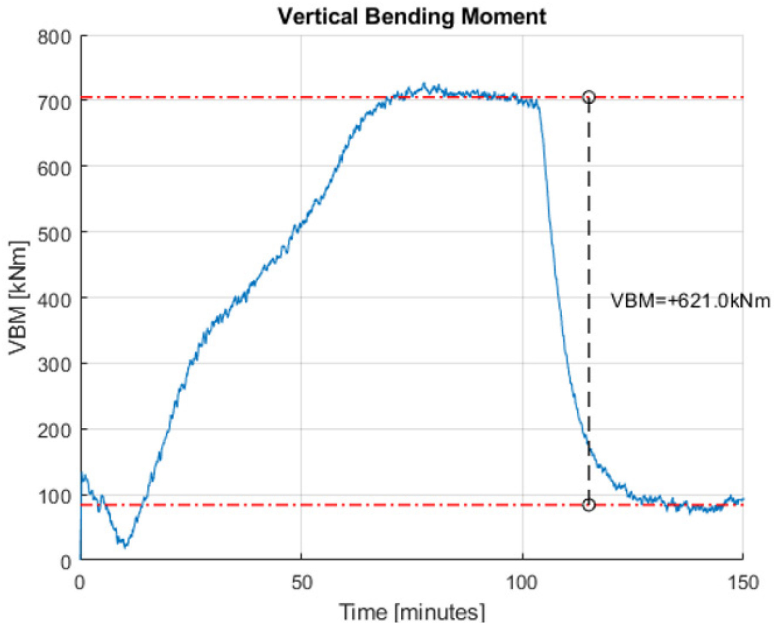

Figure 7: VBM as measured by SHMS during loading and unloading.

The test resulted in a VBM that was within the acceptance criteria of the analytical result. The digital twin representation of the vessel, providing the parameters necessary for decision support, was therefore accepted in an unmodified state.

Unlike steel vessels, where corrosive processes may modify the thicknesses and thereby the hull strength and strain distributions over time, the strength of the CFRP hull is not expected to change over time. Thus, the digital twin representation of the hull is expected to remain unchanged unless structural modifications are made.

3.2 Data Collected from Operations

During the first two years of operation, a significant amount of data has been collected, which represents the digital thread of the vessel. In addition to data concerned with the stress monitoring of the hull, the system has also offered other interesting operational information, such as speed profile, operational profile, and number of ports of calls.

Data has been collected as raw data (with strain data from each particular sensor), and as statistical data (max/min/mean/…) for 5- and 30-minute time periods respectively. The collected data is post processed and analysed by using MATLAB. Some of the results from the analysis are presented below.

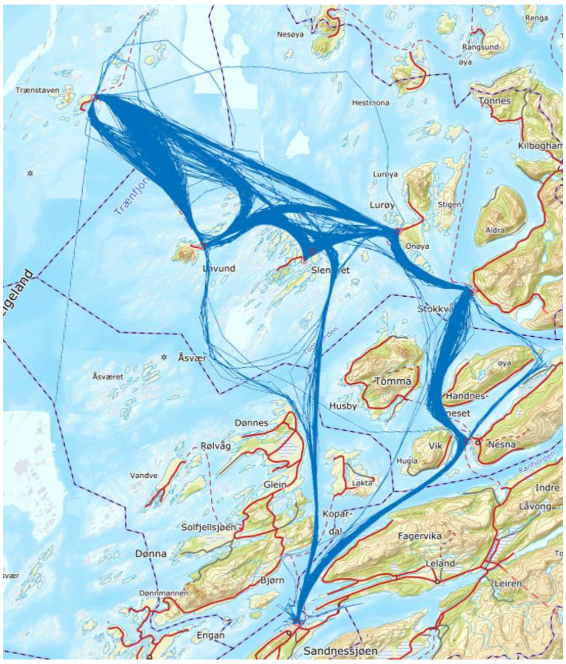

Figure 8: Operations at "Helgelandspendelen" throughout 2021.

3.3 Accelerations

3.3.1 Design Optimization and Verification Using Vertical Accelerations

When dimensioning boats based on the DNV rules, the vertical acceleration in the vessel's centre of gravity, a_{cg} or a_z, is an important parameter. Important input variables that finally derives the value of a_{cg} are vessel geometry, intended speed and significant wave height.

If the DNV rules had been followed for the vessels discussed in this paper, a design acceleration of 2.71g would be necessary for build no. 304 (with Hs = 4.0m and V = 32 knots as input variables). This rule design acceleration level means that the designer will have to use more materials, resulting in a heavier, slower, and more expensive vessel. Based on data from sea trials of similar vessels, an opportunity for optimizing the hull using a design acceleration of 1.5g was sought. The DNV rules open for this option in paragraph 2.2.3:

> *2.2.3 Upon agreement, the vertical design acceleration may be documented by direct calculations, model tests or full-scale measurements. For SWATH and craft with foil-assisted hull, accelerations shall normally be determined in accordance with direct methods.*

Figure 9: Excerpt from the DNV rules.

This is an example where monitoring data on previous vessels gives input to product development and allows for design optimization. However, a departure from the classification society rules must be justified by calculations, tests and/or full-scale measurements. This is in fact the main reason for fitting the hull monitoring system – to verify that the hull would not experience excessive loads beyond the design values, despite the lower design acceleration value. And, as part of this, the continuous measurement of the vertical acceleration to verify that the selection of design value was acceptable.

The figure below shows measurements of a_{cg} collected throughout 2022. The solid and dotted lines show the design value curves from DNV, while each dot shows the maximum acceleration detected throughout a 30-minute period.

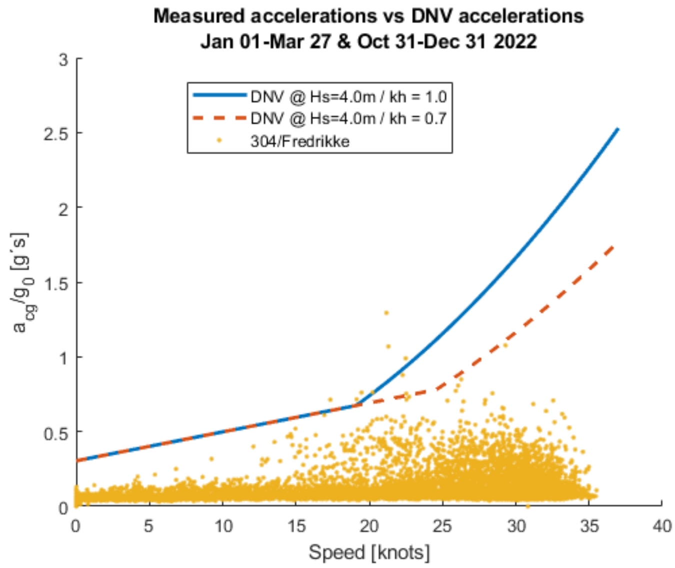

Figure 10: Vertical accelerations.

From the figure we can see that the measured (max) accelerations seem to follow the DNV curves up to nearly 30 knots. For higher speeds, the acceleration level is declining instead of increasing. The reason for this may be that the operators reduce their speed in higher sea states, avoiding high wave induced accelerations and loads. On the contrary, at about 21-23 knots we can observe a couple of accelerations above the DNV-curves. Nevertheless – no acceleration above the selected design level of 1.5g has been detected.

3.3.2 Horizontal Accelerations

In addition to vertical accelerations, the sensor also measures horizontal accelerations. The International Code of Safety for High-Speed Craft provided by IMO regulates passenger safety requirements. Three levels are defined:

- Level 1 – Minor effect: < 0.20g
- Level 2 – Major effect: < 0.35g
- Level 3 – Hazardous effect: ≥ 0.35g

Based on these requirements, the hull monitoring system will warn the crew if the IMO levels of horizontal acceleration are exceeded.

For this particular set of data, one event with horizontal acceleration above 0.35g, which has been defined as above "alarm level", was recorded. However, the system will give the crew a warning for accelerations above 0.2g, which would mean that the crew should consider asking passengers to sit down due to reduce the risk of injuries.

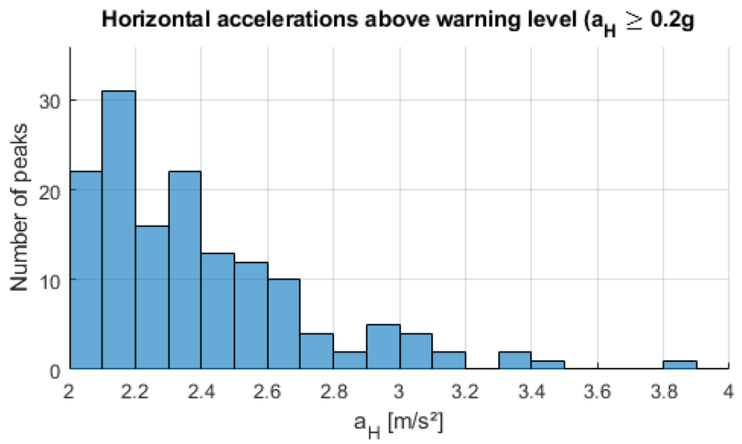

Figure 11: Number of events with horizontal accelerations above warning level of 0.20g.

3.4 Wave Profile and Indication of Wave Height

In addition to measuring accelerations and loads, the system also includes a radar that measures the distance between the wet deck and the sea surface. The purpose is to give a pre-warning if the combination of vessel motions and wave height would involve the risk of slamming. This is particularly useful during winter operations, as the darkness in North Norway makes it impossible to see the waves. The values are presented as the water elevation above the basis line of the vessel. As the wet deck height is 4.4m, the alarm level is set at 3.9m.

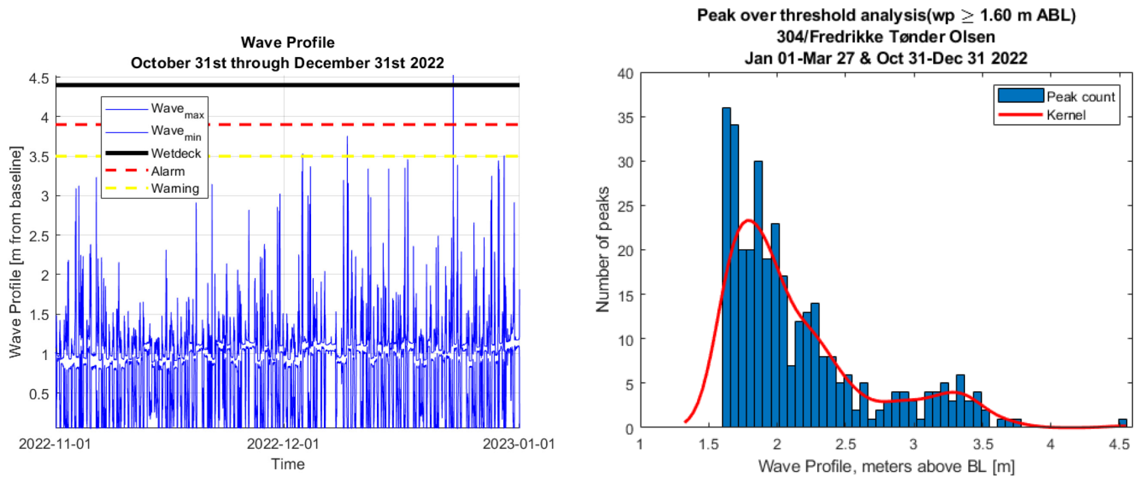

Figure 12: Wave profile.

During the last two months of 2022, just a few incidents with a wave profile above the warning level was detected, with one of them as high as 4.5m.

Another possible application of the wave profile sensor is to give an *indication* of the sea state. This was done by assuming that the maximum wave height within each 5-minute interval is the same as the double amplitude of the incident wave encountered by the vessel; $H_{Max} \approx 2 \times [(\text{wave profile}) - (\text{mean value})]$. Realizing that this method gives a rather rough estimate, it still provides useful information whether the vessel has been operating during rough or calm conditions. Results are presented in the figure below.

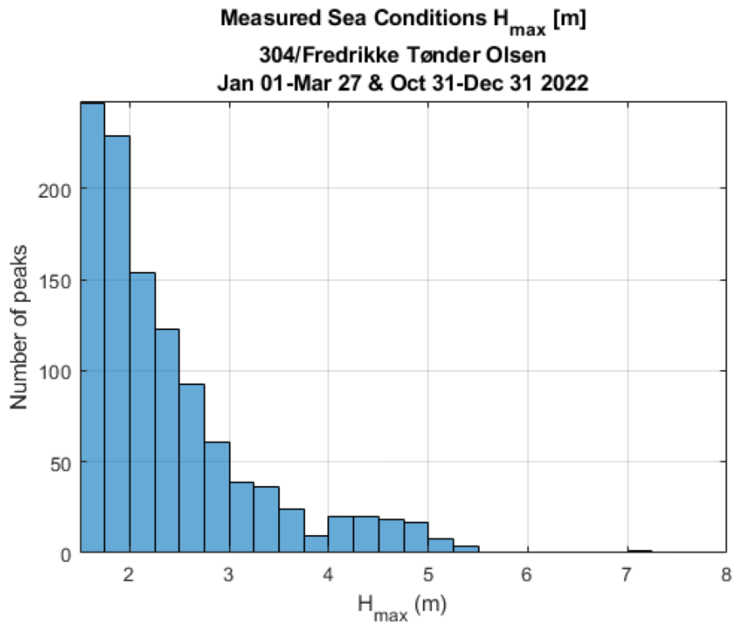

Figure 13: Sea conditions.

We can see that the vessel has been operating in conditions up to $H_S = 4.0$m (H_{Max} / 1.8) which is within the design sea state for the vessel. We can also see that the vessel mostly operates in rather calm conditions with $H_S \leq 1.5$m.

By plotting the estimated sea states against vessel speed, we may see how the vessel has been operating with respect to the operating limiting curves given in the class certificate of the vessel. Results are shown in the figure below.

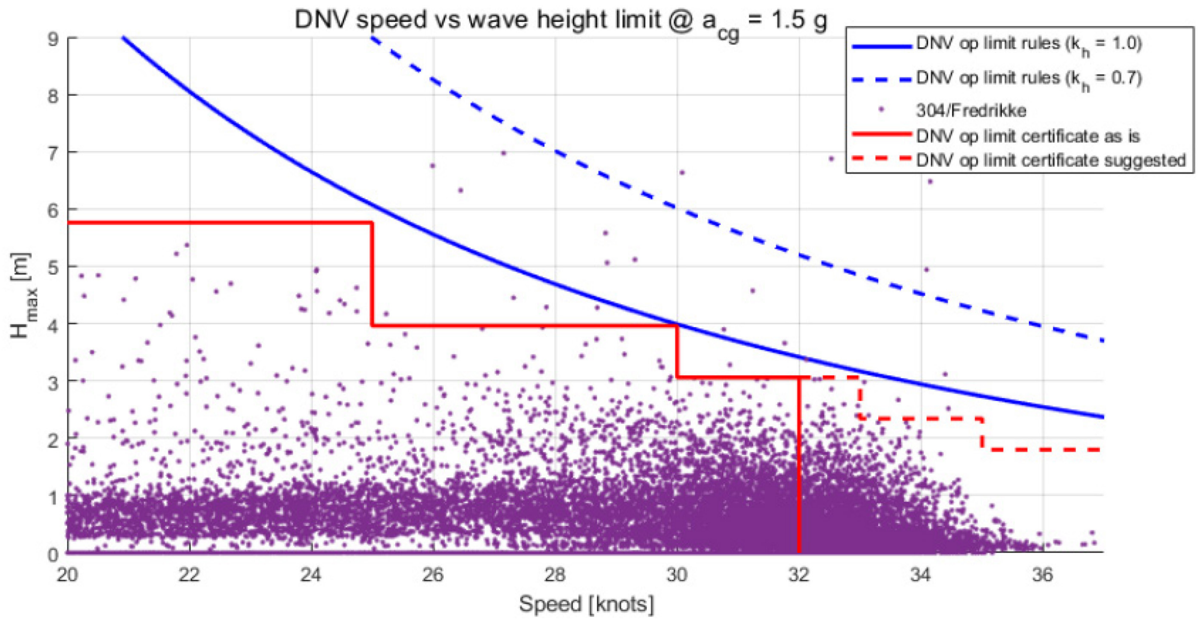

Figure 14: Combinations of observed speed and wave height*, compared to limiting curves of the certificate and class rules.

We can see that the vessel mostly is operating within the operating limiting curves given by the class certificate. We can observe, however, that the speed limitation of 32 knots in the certificate doesn't make any sense. A dotted line is added in the plot to indicate new proposed limiting values. The blue solid line indicates the "rule" limiting line based on a_{cg} = 1.5g and hull factor k_h = 1.0. We also plotted the line for k_h = 0.7 as this hull factor seems to be more suitable for these vessels due to the high wet deck height.

Even if this diagram is based on rough estimated sea states, it is considered to be much better than by visual observation of sea states only, especially when taking into account the darkness in North Norway during wintertime.

3.5 Global Loads

Figure 10 shows that the vessel has observed vertical accelerations close to the 1.5 g design level, while Figure 14 indicates that the vessel has been operating outside of the limiting curves as given by the certificate. However, exceedance of these parameters does not directly imply that the vessel has been operated in an unsafe manner. The limiting factor for hull integrity and passenger safety are the global and local loads, which are calculated and displayed in real time using the vessel digital twin.

3.5.1 Vertical Bending Moment

One of the most important parameters for global strength is the Vertical Bending Moment. Positive value represents hogging-loads, while negative values represent sagging-loads.

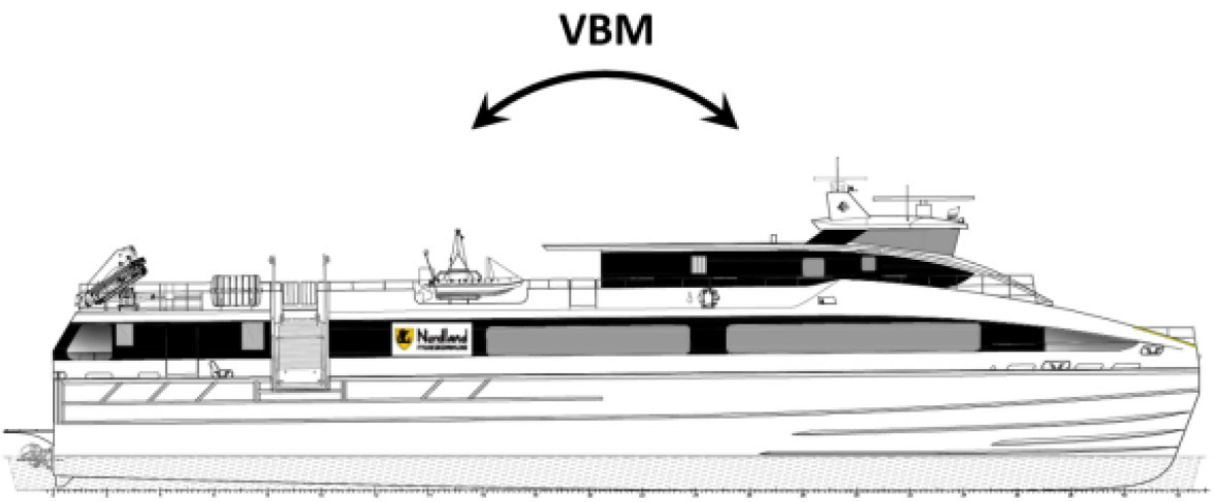

Figure 15: Vertical bending moment.

The design values for sagging and hogging are derived by two different approaches in the DNV rules. One approach considers the vessel "landing" on a wave crest or wave hollow, while the other approach considers geometry and displacement only.

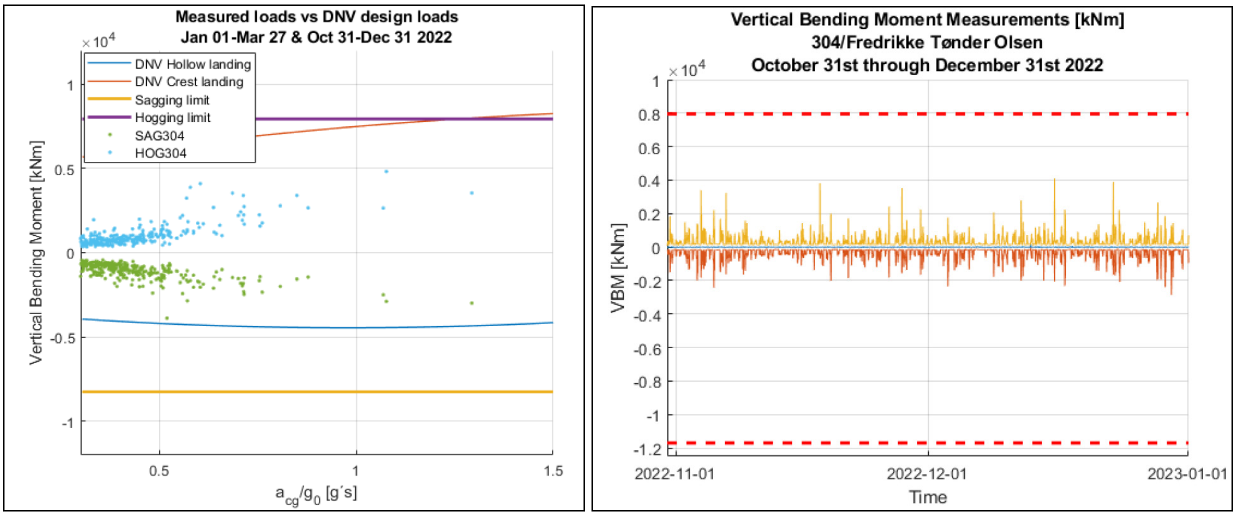

Figure 16: Design loads from DNV rules, applied structural limit loads, and measured SAG and HOG on one of the three vessels throughout operations in 2022. We can see that the loads are well within the limits.

From the figures above, we can see that measured hogging and sagging loads are well within the design values even when the vertical acceleration values approach the design acceleration level.

3.5.2 Torsion Moment

Another important parameter for global strength of a catamaran is the torsion moment. When considering torsion moment based on DNV rules, the pitch connecting moment is considered, as this gives the most conservative values.

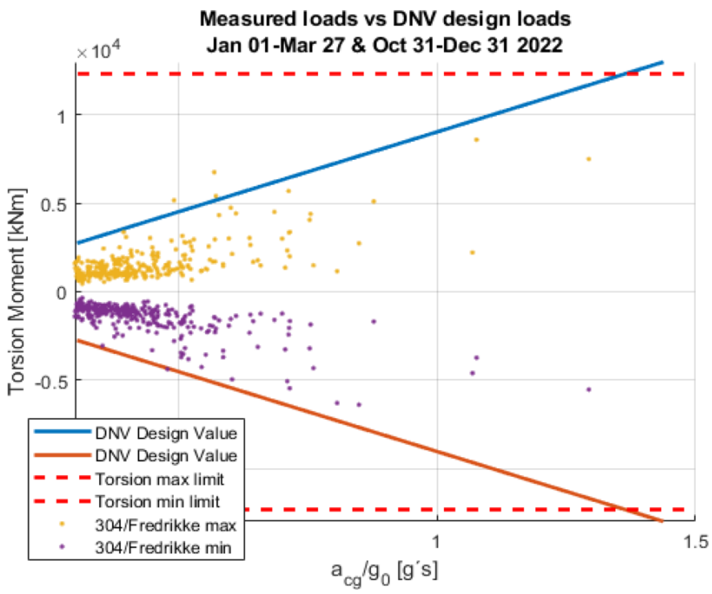

Figure 17: Torsion loads.

We can see that the maximum torsion moment recordings are following the DNV-curves up to about 1 g, before levelling out. Nevertheless, the measured values are far below the limit load values applied in the design.

3.6 Slamming Loads

The vessels are equipped with strain sensors on the wet-deck panels forward to detect whether those are subjected to slamming loads. Due to the very high wet deck height of this design, almost no slamming has been detected in the bow area. However, by application of two of the sensors of the sensor array amidships (BT1 and BT2), multiple events of bottom slamming amidships have been detected.

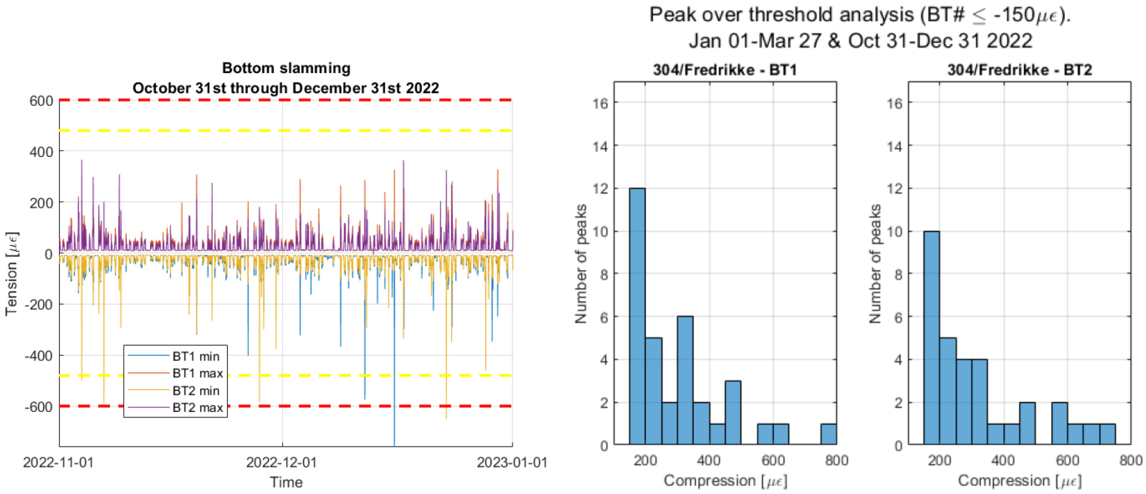

Figure 18: Slamming loads.

The figure shows that the vessel has been subjected to multiple bottom slamming events. We can see that the largest values are negative, which means compression of the beam with the sensor fitted. This is most likely due to crest landing incidents. Even though the alarm limit values have been exceeded, no damage to the hull girder is anticipated as the global load level (VBM) still are within the applied design values.

4.0 CONCLUSION

In this paper, we have sought to demonstrate, through a practical application to a civilian fast ferry operating in the rough seas outside Northern Norway, how the combination of a SHM system and a digital twin has enabled a leaner, faster, and cheaper vessel compared to a design using the a priori knowledge represented by the class design rules.

We have shown that direct measurement of the global limiting loads and accelerations by the ship hull monitoring system is a much better tool to ensure operation within the design limits than the operation envelope given in the class certificate. This is to be expected, as the SHMS gives an objective measurement of the limiting loads while the operation envelope relies on indirect parameters, as the vessel speed, and subjective assessment of the significant wave height.

Furthermore, the years of data collected by the SHMS allows establishing predictive models for the limiting parameters, providing a pre-warning of load exceedance risk during operations, and allowing the captain to run what-if scenarios to aid the decision of whether to commence planned crossing or not.

With appropriate user instructions, it should hence be possible to use the operator guidance provided by the hull monitoring system instead of the limitation curves in the certificate. Based on this, we may conclude that the ship hull monitoring system will increase the regularity of the vessel as the vessel may be safely utilized during conditions beyond those given in the class certificate.

In addition, the digital twin allows detailed analysis of any future load exceedance events, providing indications of when and where to inspect for possible damages, potentially reducing inspection and maintenance cost while increasing the overall safety and integrity of the structure.

Although the subject of this study has been a civilian fast ferry, the methods presented are of equal importance to several military platforms for, e.g., developing an efficient maintenance program, fatigue management of a ship or ship class, applied to surface vessels, submarines and unmanned vessels. We have seen that post processing of data collected for the particular application offers lots of possibilities for presentation of load history and statistical analyses, and that such analyses may be tailored for the application in question.

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