Concept note

SENSFIB
Ice Load Monitoring System

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1 SUMMARY OF CONCEPT

Light Structures proposes Ice Load Monitoring Systems (also known as Ice Response Monitoring) by using short-base fiber optic sensors detecting and characterizing the forces acting on the stiffeners during operations in ice infested waters by measuring stress, primarily as shear stress, in key positions.

All monitoring will be logged and processed using Light Structures' extensive SENSFIB software suite.

The SENSFIB system is ATEX certified, and hence can be applied also on ships with hazardous areas.

The major classification societies all provide guidance on how to arrange sensors for Ice Load Monitoring, however they leave the scope of monitoring to the owner in collaboration with hull designers and instrumentation supplier. Different configurations and scopes of monitoring are provided for illustration purposes.

More detailed technical proposals will be given on project to project basis.

2 INTRODUCTION

2.1 SENSFIB Fiber Optic Monitoring Systems

The *SENSFIB* system was originally developed for ship hull monitoring and is increasingly applied also for moored offshore structures. The system promotes a good and safe operation of the hull. This is achieved by measuring the strain (hull load) in key locations. *SENSFIB* is the most advanced hull monitoring system available, and the dominating fiber optic hull monitoring system world wide.

The core technology is based on patented fiber optic sensing techniques, originally developed by Light Structures personnel for Naval/Military purposes.

- the sensor is all-fiber optic, and contains no electrical parts or electrical wires
- the fiber optic sensor is intrinsically explosion safe, and requires no special EX packaging for use in hazardous areas
- fiber optic sensors do not short-circuit when in contact with water
- the fiber optic transmission cable, linking the sensor to the central unit, is completely passive. Thus, the measurements are not marred by cable temperatures or pickup of noise from nearby electrical wires.
- the sensor may be placed in submerged locations, i.e. inside ballast tanks.
- fiber optic signals have an unsurpassed long-term stability
- the fiber optic components are based on standard telecom components, built for a

long life

These factors contribute to high quality measurements that give precise information on the hull conditions.

The system may operate on strain sensors alone, or may be interfaced with other systems according to class and owner’s requirements, such as:

- Loading computer (on-line mode)
- GPS / time server
- Wind sensor
- Wave sensor
- Motion Reference Unit (MRU)

2.2 Hull Info for onshore hull management

All parameters that are measured by *SENSFIB* are saved for later analysis. The data files may be exported to backup media (usually USB memory/disks) for analysis onshore, or sent to shore at fixed intervals using a satellite or cable data link.

3 SENSFIB ICE LOAD MONITORING (ILM) SYSTEM

Several research projects have been carried out over the past 10-15 years, and they have implemented different concepts for monitoring the hull response to impacts from ice at the Ice Water Level and below. In recent years a number of system have been installed for operational guidance and not just for information gathering. The experience from these projects points to instrumentation of frames as the most effective configuration even though other supplementary arrangements are mentioned in guidance from major classification societies.

For information gathering one will often concentrate the instrumented frames to one side of the hull, either port or starboard, and rely on statistical analyses to accumulate and analyze a dataset that is considered to have validity for both sides over a logging period of some years. However, as an operational tool for the navigators, Light Structures recommend a symmetric installation to be able to offer some guidance independent of the operational pattern. This is discussed futher in chapter 4.

It is fairly common to supplement these local sensors at the IWL with sensors that monitor the global bending (sagging/hogging moment) during blue water transits as well as during operations in ice infested waters to characterize the overall loading of the hull girder.

Furthermore, it is recommended to record operational information from interfaces to navigation system and engine control, such as position and speed over ground (GPS), speed through water (speed log), RPM, power, torque and thrust (engine control), heading, (gyro compass), roll and pitch (if available from MRU or gyro) and wind.

Another type of supplementary instrumentation is the addition of one or more motion sensors to characterize the rigid body impact of hull-ice interaction. The global effect can be found from a Motion Reference Unit, while the local area effect in the bow can be found from a tri-axial accelerometer in the forepeak.

3.1 Basic ILM – shear stress in frames

The basic solution measures the shear in frames to evaluate the forces from ice interacting with the side shell structure at the Ice Water Line (IWL). Each instrumented frame is fitted with a shear stress sensor mounted at the upper end of a frame (above the IWL) and one at the lower end of the same span, below the IWL, see illustration in Figure 3.1.

If there is interest in tracking ice being pushed under the hull there is an option to install sensors also in a lower elevation, below the waterline.

The recommendation is to instrument *intermediate frames* that have a reduced web height compared to web frames, in order to measure the higher stress levels. For hulls (or parts thereof) that are *longitudinally stiffened*, the instrumentation is fitted on longitudinals rather than frames.

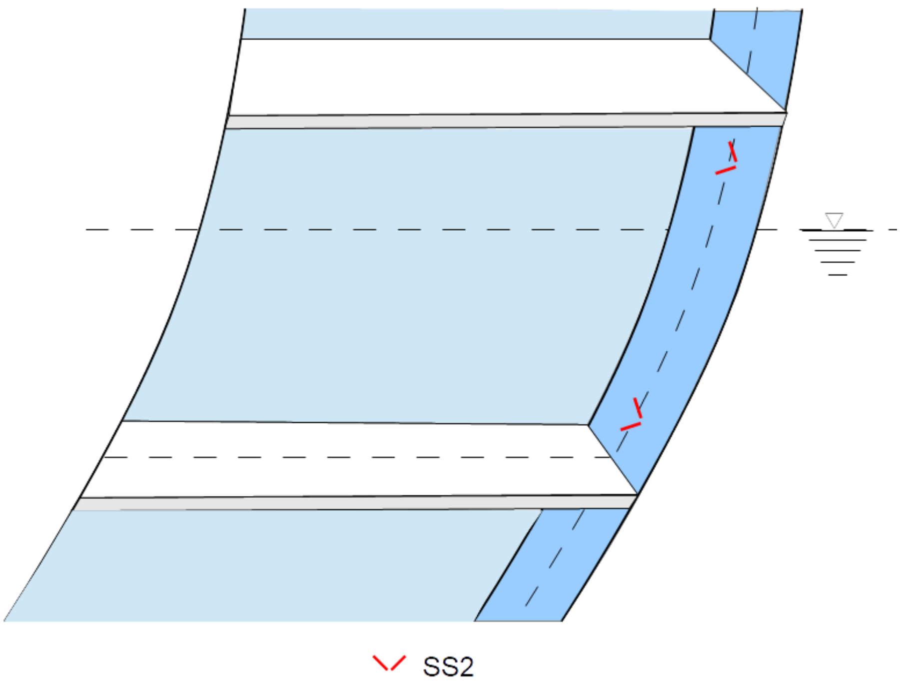

Figure 3.1 Illustration of concept – not corresponding to actual structure onboard.. The instrumented frame is fitted with a shear sensor above and below the ice waterline level..

This concept for Ice Load Monitoring is similar to the frame instrumentation on the instrumentation on vessels such as the “Sir David Attenborough” for the British Antarctic

Survey and "Kronprins Haakon" for the Norwegian Institute of Marine Research. It corresponds to the recommended arrangement from DNVGL and LR.

In order to gain the full benefit from an Ice Load Monitoring system it is essential that the hull structure is analyzed in detail to ensure that the sensor positions are optimized for the design to pick up the most relevant and critical stresses. Furthermore a set of response factors and capacity limits are required in order to evaluate the actual loading against the stiffness and resilience of the structure. This is normally outside the scope of supply from Light Structures. However, Light Structures are collaborating with Aker Arctic for the supply of such analysis services if the Customer does not wish to carry out the calculations themselves.

3.2 Additional sensors for frame bending

The next level of instrumentation includes normal stress sensors to characterize the bending of the intrumented frames. Each of the locations are fitted with a pair of shear sensors SS2 on an intermediate frame and a bending sensor SS1T on the midpoint of the frame,

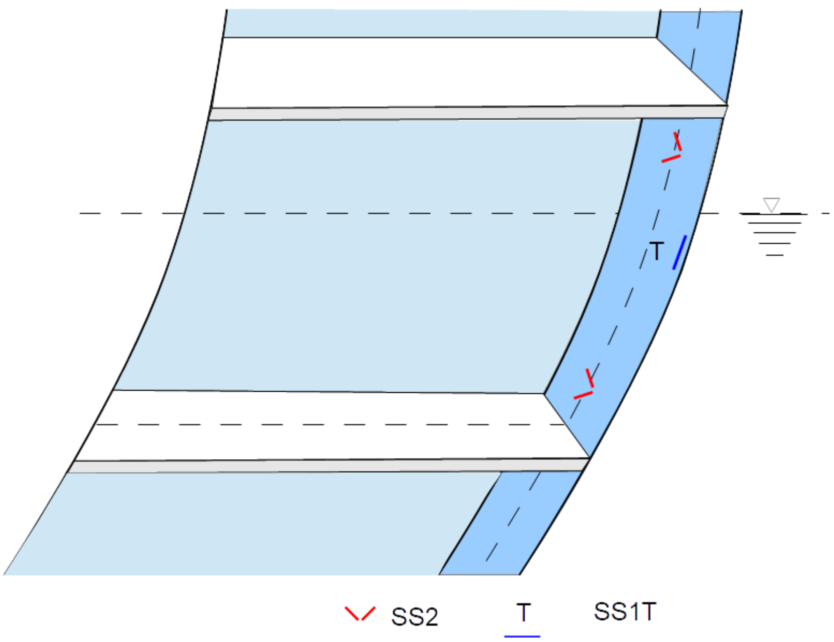

Figure 3.2 Illustration of principle of sensor position – not corresponding ot actual structure onboard.. The instrumented frame is an intermediate frame fitted with a shear sensor above and below the ice waterline level. The instrumented side longitudinal on the other hand will have shear sensors fitted near the bounding web frames. Intermediate frames not shown here. Both the intermediate frame and the side longitudinal will have a bending sensor fitted on or near the flange of the stiffener.

The use of a supporting normal stress sensor for frame bending is recommended by ABS and mentioned as an optional extension by LR.

The strain gauges on a frame are temperature compensated using the local temperature at the midpoint. Similarly, strain gauges on a longitudinal are temperature compensated using the local temperature at the midpoint of the longitudinal.

3.3 Additional sensors for plate fields

The scope of monitoring for ice load monitoring systems (ILM) recommended by BV rules, which we have interpreted in Figure 3.3 includes a rosette gauge in the middle of plate fields in addition to the instrumentation in section 3.2.

Each of the locations are fitted with a pair of shear sensors SS2 on an intermediate frame and a bending sensor SS1T on the midpoint of the frame. BV actually recommends instrumenting up to five adjacent frames, to monitor a *load patch,* but single frame at each location is also accepted.

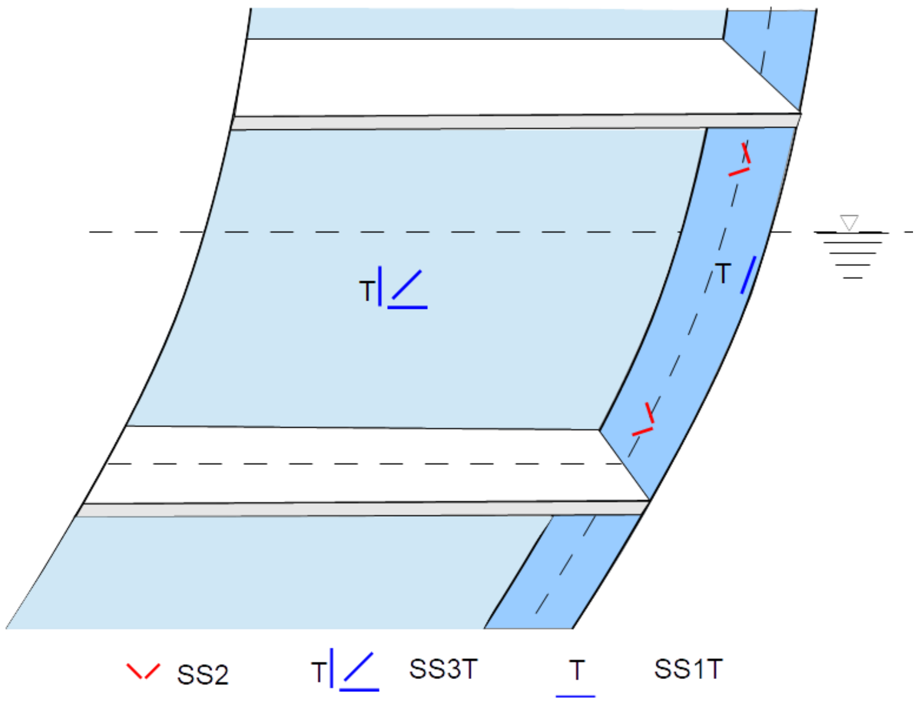

Figure 3.3 Illustration of principle of sensor position – not corresponding ot actual structure onboard.. The instrumented frame is an intermediate frame fitted with a shear sensor above and below the ice waterline level. The instrumented side longitudinal on the other hand will have shear sensors fitted near the bounding web frames. Intermediate frames not shown here. Both the intermediate frame and the side longitudinal will have a bending sensor fitted on or near the flange of the stiffener.

For this arrangement the strain gauges on a frame are normally temperature compensated using the local temperature at the midpoint, while the rosette gauge has its own local temperature compensation.

3.4 Monitoring of frames and longitudinals

The most comprehensive solution for ILM systems is interpreted in Figure 3.4. Each of the locations are fitted with a pair of shear sensors SS2 on an intermediate frame, a bending sensor SS1T on the midpoint of the frame, a pair of shear sensors on a side longitudinal, a bending sensor on the midpoint of the side longitudinal (between web frames) and finally a three-axis rosette SS3T in the center of the plate field near the side longitudinal midpoint.

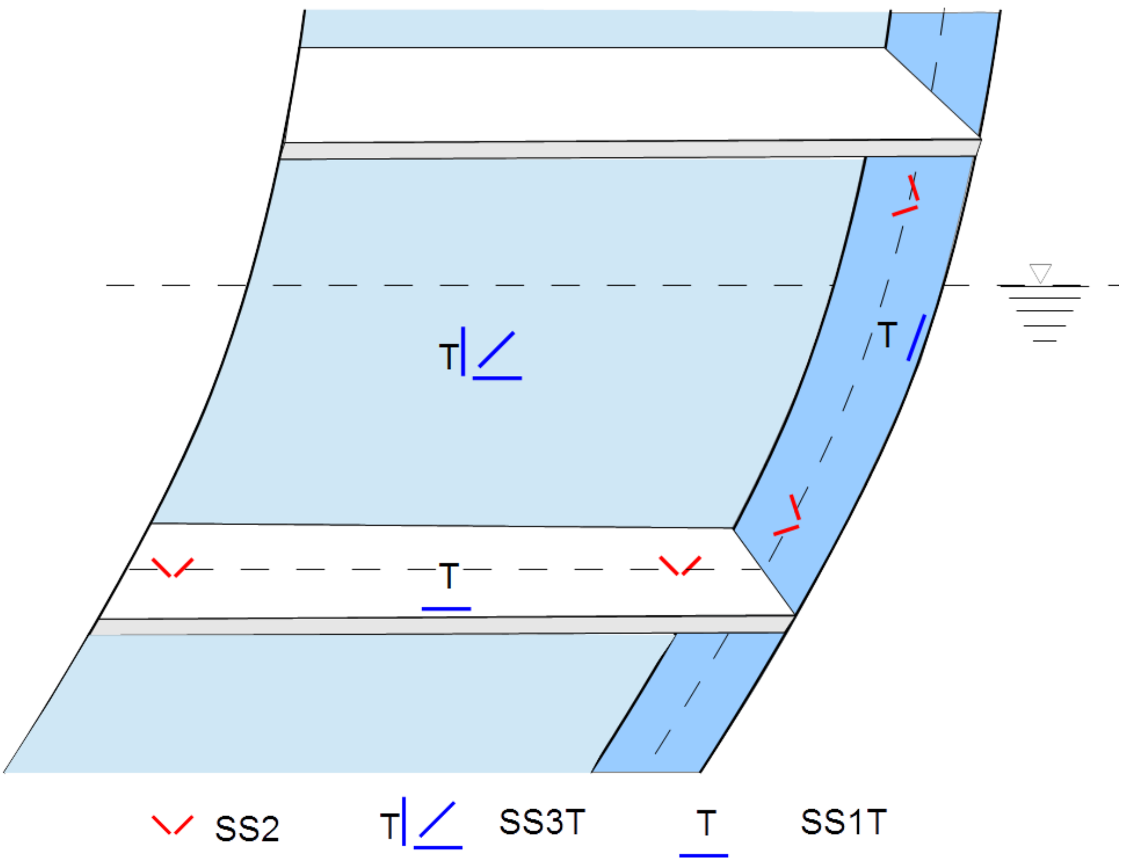

Figure 3.4 Illustration of principle of sensor position – not corresponding ot actual structure onboard.. The instrumented frame is an intermediate frame fitted with a shear sensor above and below the ice waterline level. The instrumented side longitudinal on the other hand will have shear sensors fitted near the bounding web frames. Intermediate frames not shown here. Both the intermediate frame and the side longitudinal will have a bending sensor fitted on or near the flange of the stiffener.

The strain gauges on a frame are temperature compensated using the local temperature at the midpoint. Similarly, the strain gauges on a longitudinal are temperature compensated using the local temperature at the midpoint of the longitudinal.

For the bending response of the plate field a three-axis rosette is placed centrally in the plate field and near the waterline. A three-axis rosette enables us to find the full in-plane stress condition in the panel. The SS3T sensor comes with a built-in temperature sensor for compensating the strain signals with the local panel temperature.

4 SYSTEM CONFIGURATION

4.1 Choice of instrumented locations

As mentioned in the introduction the classification societies offer limited guidance on the overall scope of measurement. The determination of number and locations of instrumented frames (or longitudinals or combinations thereof) is left to the ship owner or designer. The intended usage of the results should be taken into consideration when a scope is selected.

4.2 Single sided or symmetrical instrumentation

For information gathering and processing onshore one will often concentrate the instrumented frames to one side of the hull, either port or starboard, and rely on statistical analyses to accumulate and analyze a dataset that is considered to have validity for both sides over a logging period of some years.

If the shipowner intends to use the system as an operational tool for the navigators, Light Structures recommend a symmetric installation to be able to offer some guidance independent of the hour-by-hour operational pattern.

4.3 Single frame per location or multiple consecutive frames

Some systems include instrumentation of multiple consecutive frames. This will allow hull structure expertise onshore to analyze in more detail how the ice loads are distributed over a load patch, and on that basis make recommendations on operational patterns and maintenance planning.

For operational guidance it is more common to instrument a single frame per location to allow monitoring of a larger portion of the waterline for a given budget.

4.4 Number of locations and their distribution along the waterline

For vessels that will predominantly be operating in a broken channel or break ice itself in a forward operating mode, the sensors are concentrated in the bow and/or bow shoulders.

For vessels that may execute turns in ice, we recommend that the system is extended to include additional sensors for midships and the stern, in order to characterize ice forces during turns.

Double-acting icebreakers would concentrate sensors in the stern where the main ice-hull interactions are expected during ice breaking operations.

4.5 Hull monitoring for blue water operation

Some ILM systems include hull stress monitoring and slamming montoring sensors.

Hull stress monitoring sensors are installed on main loadbearing longitudinals under the main deck, and will measure stresses due to sagging-hogging moments during operations in elevated seastates in open waters as well as sagging moments that can arise during ramming in ice.

Some bow designs leaves the vessel more prone to bow slamming, and a vertical accelerometer in the fore peak will record number and magnitudes of slamming events. Some systems include additional accelerometer in the longitudinal and transverse directions to characterize accelerations due to ice impacts in more detail.

4.6 Supporting data and interfaces to ship systems

For a better understanding of the hull-ice interaction it is recommended to record operational information. This information is normally available from interfaces to navigation system and engine control. The following parameters are of interest:

- position and speed over ground from GPS/DGPS/GLONASS
- speed through water from the speed log
- RPM, power, torque and thrust from engine control
- heading from gyro compass
- roll and pitch from MRU or gyro (if available)
- wind.

Light Structures can supply OEM sensors for shaft torque and thrust monitoring as well as a 6 degrees-of-freedom Motion Reference Unit if these are not available for interfacing.

5 SCOPE OF SUPPLY

The detailed scope of supply is subject to individual project proposals after considering the different aspects of system design and configuration as discussed in the above. However, the system will typically consist of:

- A number of ILM sensors in each of a number of locations
- Fiber optic cabling from each sensor in a location to a junction box
- Fiber optic trunk cabling from junction box(es) to a central processing cabinet
- Central processing cabinet in instrument room, electrical equipment room or similar with sensor interrogator, processing PC and software for processing and Graphical User Interface
- Uninterruptible Power Supply or Automatic Transfer Switch
- System display and work station at the system cabinet and/or on bridge

5.1 Functions provided by software

The SENSFIB software includes a wide range of functionality to do as much processing as possible onboard and in real time, in order to reduce the amount of manual processing necessary onshore.

In addition to logging time series the software will identify and characterize ice-hull interaction events based on the hull data provided by the Customer, see chapter 6. The presentation onboard uses the alarm limits and displays all impact magnitudes in terms of a percentage of the hull strenght in each location. The saved data are recorded as MPa in order to facilitate more detailed analyses onshore.

Statistics are calculated for every parameter available in the system, and provides an effective way of getting an overview of which logging periods contain data of interest.

The saved data include

- Storage of down-samples time series for onshore analysis
- Statistics calculations (5 minute and 30 minute stats on max, min, average, standard deviation, skewness and kurtosis)
- Histograms of maxima and minima
- Residual strength/utilization calculations based on impact stresses
- Online fatigue analysis with Rain flow counting and Miner's sum calculation of damage parameters
- Digital filtering to separate wave driven loads and vibrations (e.g. whipping/springing)

Data are stored in ASCII or a proprietary binary format, depending on file type and content. All files contain headers that detail the format and contents of the file.

5.2 Examples of Human Machine Interfaces

The information that is provided to the user is taylored to match the actual scope of monitoring and the intended usage of the system.

For systems that are intended primarily for information gathering and onshore post-processing, a very limited user interface is required onboard, mainly focused on providing system and sensor status information and a front end for exporting data for transfer to shore (when done by physical medium such as an external hard disk).

Systems with operator guidance functions will present more detailed information on the magnitude of measurements related to alarm limits for hull capacity. However, how this is done depends on the actual scope of montoring and requirements from the Customer. Some examples are provided in the below.

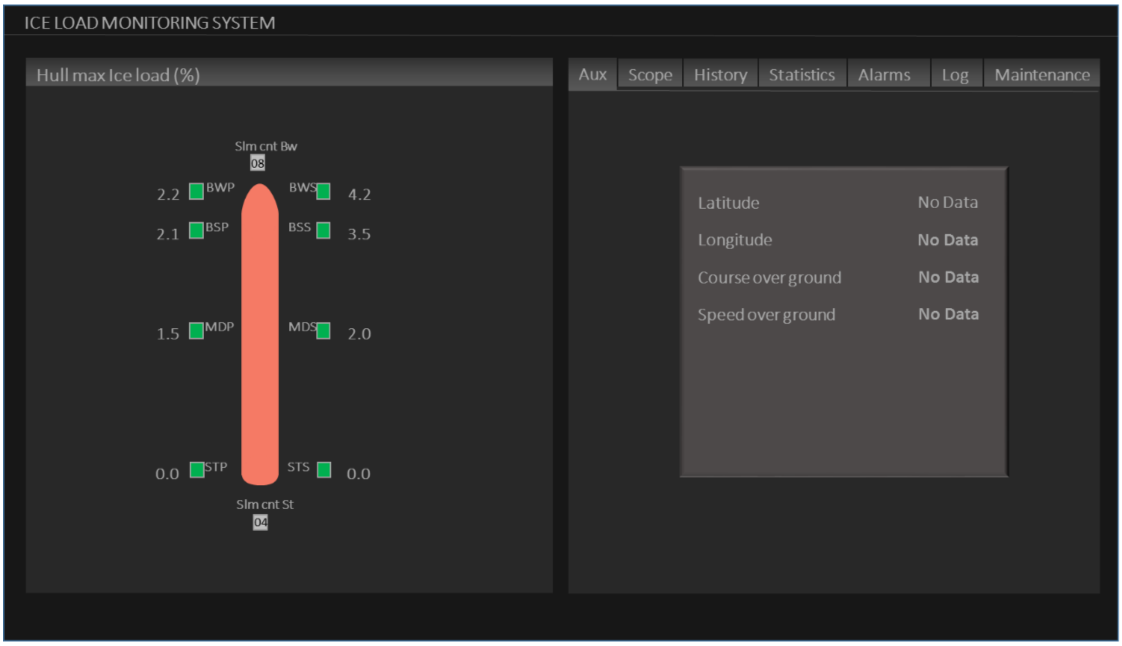

Figure 5.1 Simple Ice Load Monitoring user interface showing the overall load at each instrumented frame. Also showing information received from navigation system (GPS).

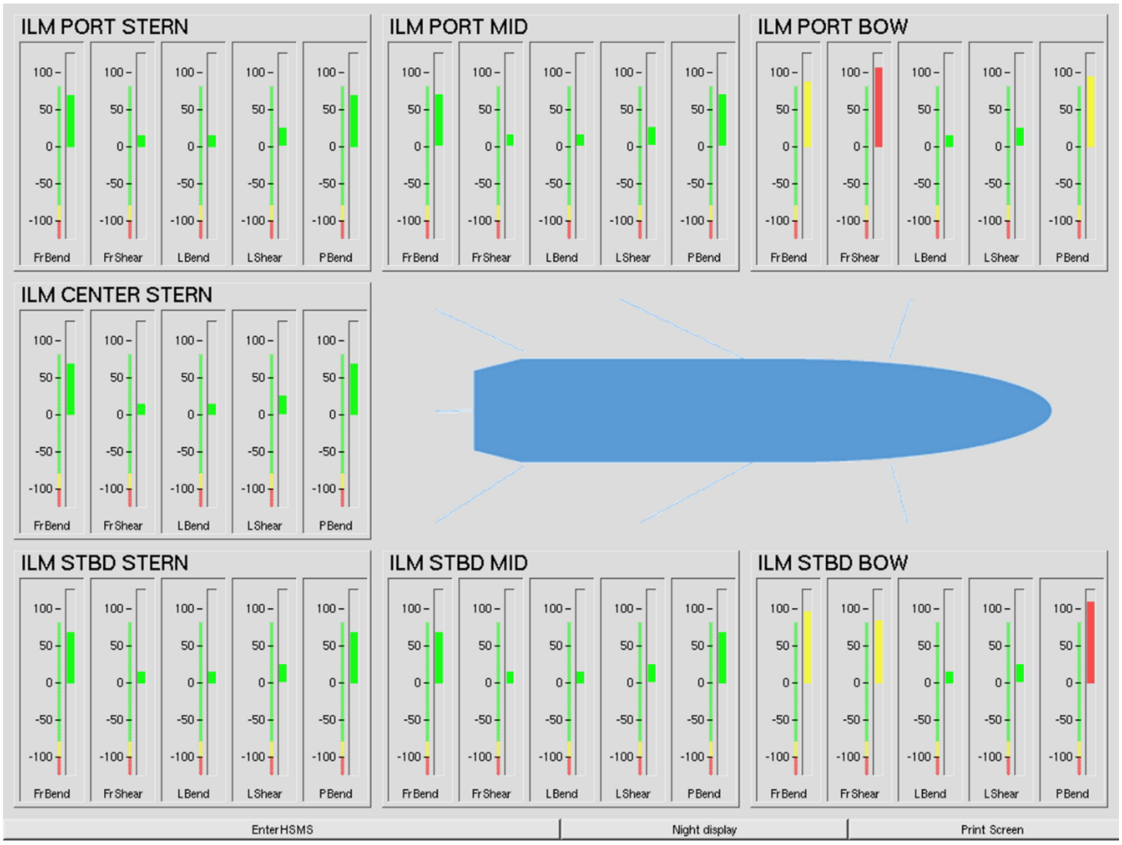

Figure 5.2 SENSFIB HullInfo example view for comprehensive Ice Load Monitoring systems showing utilization in individual frames

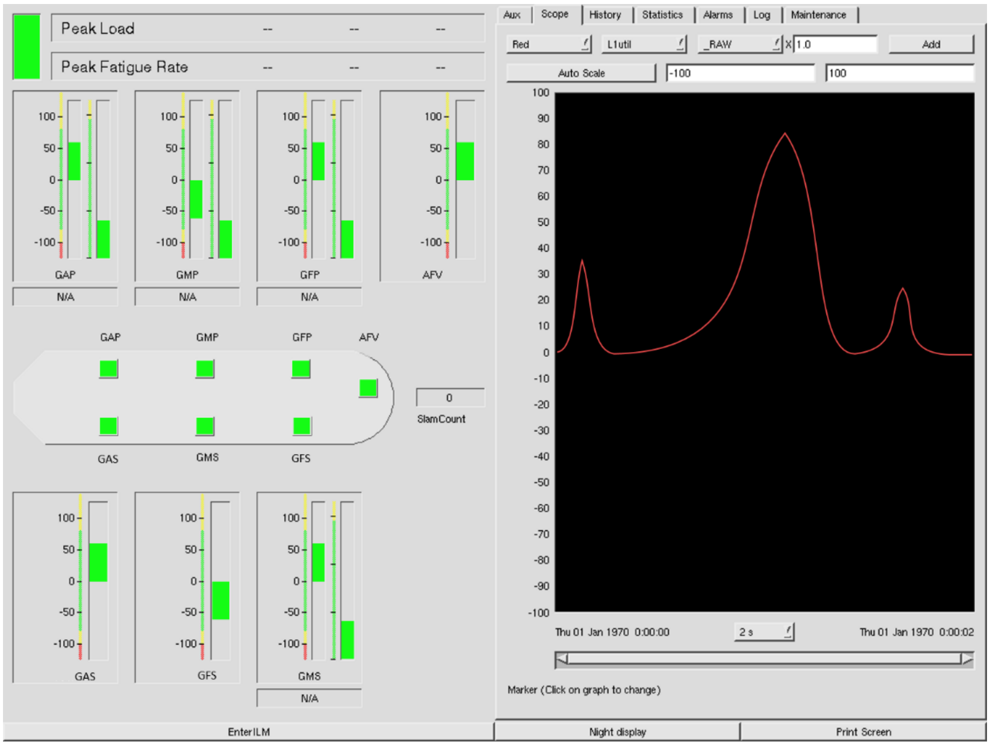

Figure 5.3 *Hull Stress Monitoring view with scope function that shows the detailed time trace of ice load impacts to the right.*

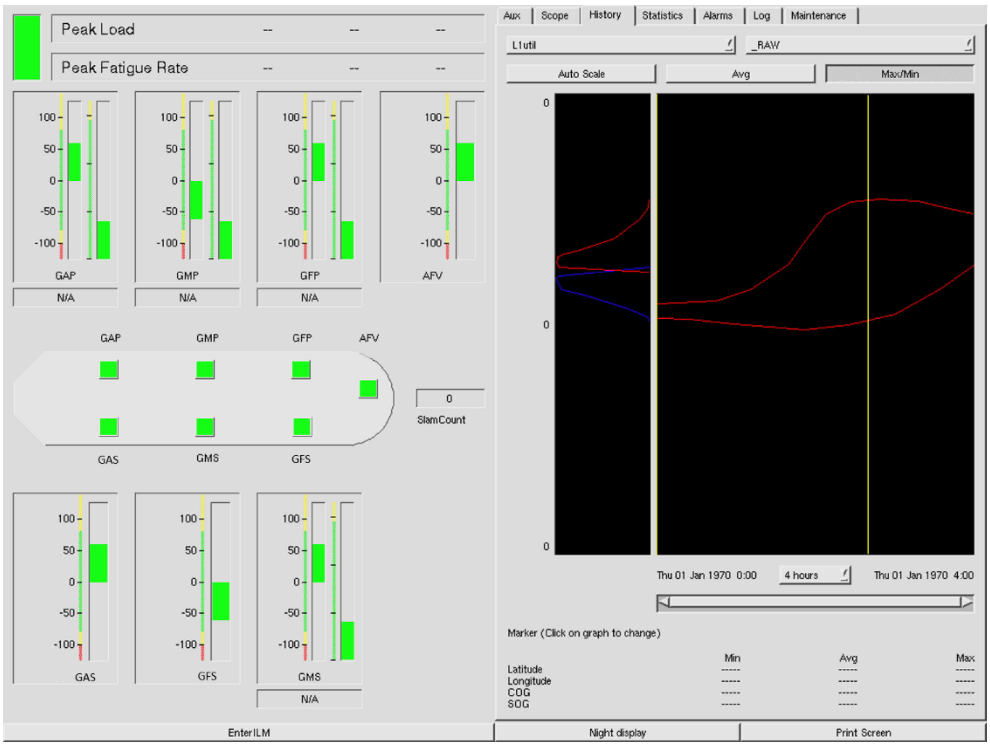

Figure 5.4 History view to the right, including display of the distribution of maxima and minima

6 TECHNICAL REQUIREMENTS – YARD/CUSTOMER SUPPORT

Yard/customer to provide all relevant hull data for the system, including the response factors and capacity alarm limits for frames.

Scope of installation services from Light Structures is based on Customer providing mechanical installation support as follows:

- Yard/customer to prepare penetrations through watertight bulkheads
- Yard/customer to install all cables (fiber optic and cables to connected systems), support for cables and cable penetrations to WBT.
- Yard/customer to prepare all surfaces for short base sensor mounting (strip paint and sand surface), and paint sensor locations after finished installation.
- Yard/customer to provide heating arrangements if steel temperatures are less than 10°C during short base sensor mounting.
- Yard/customer to provide and erect scaffolding, where necessary, for safe conduction of LS field engineers work

7 SYSTEM PERFORMANCE AND VERIFICATION TESTING

The operational performance of an ILM system will rely on a combination of the quality of:

- Equipment
- Installation
- Response factors and alarm limits for the capacity of the hull
- Implementation of response factors in processing software
- Zero-setting, or definition of stress offset values at commissioning (if alarm limits are defined for static or quasi-static stress)

7.1 Equipment and software verification

The quality of equipment is normally verified through type approval or other laboratory testing to confirm the accuracy and sensitivity of sensors and instruments.

The quality of installation is normally verified by inspection against a documented and pre-defined installation procedure which may or may not be a part of the type approval documentation.

The correct implementation of software can be verified by testing with synthetic data, i.e. when values for a known situation is used as input to the software, the expected outputs are generated.

There are some challenges associated with testing the validity of response factors and alarm limits. These should be generated from the hull design models, and ideally represent an ensemble average of a set of different load cases (ice impact centered on frame, on plate field, on midpoint of longitudinal, etc.).

There is furthermore challenges associated with arranging application of test loads (with hydraulic jack for pushing or tackle for pulling) in such a way that they match a modelled load case. One possibility could be to model a test case and run the system on a special "test case software configuration" rather than using the "operational" configuration with response factors based on an average of different load cases.

One well defined special load case could be to use the hydrostatic pressure from two different draught conditions to generate a uniform, static pressure on the instrumented panel. The test would have to be done without ballast water in the tank in question, but other than that it should be possible to gather data by letting the system run while the ship was going through other tests that included light-ship condition and a loaded condition.

7.2 Permissible stresses – definitions and zero-setting

Alarm limits are defined from analyses of local, detailed structural model, and should represent permissible stress levels in the stiffeners and plating for a set of different loads against the hull.

At the core of "permissible stress" is the yield stress of the material / construction steel. However, it is not advisable to plan on utilizing the full 350-400MPa capacity of the material due to residual stresses from construction as well as safety margin. Even if a major effort is made at detailed engineering stage to analyze a large set of load cases, it is not realistic to define and analyze every possible way that ice can excert force on the hull.

Some key elements that affect the total budget for permissible stress due to ice loads:

- Residual stress from steel cutting
- Residual stress from local welding as well as block welding
- Safety margin to account for load cases that give a higher hotspot stress than those included in the ensemble average
- Stress contribution from ballasting condition at time of zero-setting (if done after launch)

Some Ice Load Monitoring systems are set up to consider only dynamic stresses, i.e. applying a highpass filter to the measurement data and look only at the short duration stress peaks and their amplitude. This removes the requirement for defining a zero-level, but is not a good approach for ice breakers where there could be a more long-term quasi-static component to the ice loads. For vessels with ice class but no ice-breaking operational pattern this is the recommended approach, as ice impacts will be due to floating ice in an already broken channel.

For ice-breakers a different approach must be agreed for zero-setting and verification of analysis results and alarm limits.

In order to gain the maximum control of this, ideally the steel should be fitted with strain sensors before steel cutting. However, this is not practical as the sensors are sure to be damaged in the course of construction. Hence an approach must be found that is based on sensors being fitted in late stage production.

One approach to handling the uncertainties mentioned above is to define a fairly high safety margin when defining the permissible stress levels, i.e. setting alarm and warning limits with safety margin, and define “zero” for the ice load sensors to correspond to light-ship condition when ship is floating with minimal external water pressure and zero internal water pressure.