POAC'13
Espoo, Finland

Proceedings of the 22nd International Conference on
**Port and Ocean Engineering under Arctic Conditions**
**June 9-13, 2013**
**Espoo, Finland**

# LIMIT STATE IDENTIFICATION FOR ICE-STRENGTHENED HULL STRUCTURES USING MEASURED LONG-TERM LOADS

Pentti Kujala [1], Sören Ehlers[2]
[1]Aalto University, Espoo, FINLAND
[2] Norwegian University of Science and Technology, Trondheim, NORWAY

## ABSTRACT

Safety of ships and economic shipping in ice is becoming more and more important since the traffic in ice-covered waters increases and ice-induced damages requiring repair continue to occur. Consequently, this paper will present the influence of the design load level to the probable repair cost following long-term load. Hence, the aim is to identify optimal scantlings following the chosen design load, which minimize the lifetime costs for ship construction and operation. As a case study MS Kemira's hull structure and therewith-measured long-term loads are used to evaluate the sensitivity of the load level with varying occurrence frequency to the production and repair cost. As a result, we will be able to identify the optimum structure by means of production and probable repair cost.

## INTRODUCTION

During an average winter every Finnish port and every Swedish port north of Stockholm is ice bound. Furthermore, every port in Estonia is ice bound during an average winter. Thus, the Finnish-Swedish winter navigation system has been developed, because economical feasibility of the ship-based import and export depends on safe winter navigation through the ice-covered waters for these countries in the Baltic Sea. However, this economical feasibility conflicts with the ship design criteria, as the current FSICR accepts a certain level of damage, see e.g. Kujala (1991), and Hänninen (2005). Additionally, the cost of the escorting ice breaker fleet of each country is covered by the vessels' harbour fees, which decrease with increasing ice class. Hence, these fees are subjected to variations depending on the distribution of ice classes found on the vessels in each year.

Recent studies (Kaldasaun and Kujala, 2011, Riska and Kämäräinen, 2011) have shown that all the current ice class rules, i.e. Finnish-Swedish Ice Class (FSICR), IACS Polar Class (PC) and Russian Ice Class (RMRS) rules, accept some plastic deformation as the design limit states. The amount of allowable plastic deformations is not clearly defined in any of the ice class rules. Hence, the aim of this paper is to study the possibility to define the allowable plastic deformation based on the requirement to repair a probable damage structure following ice impacts. Typically, the plastic deformations on ice-going vessels cause some small local dents on the plating or frames without any risk for cracks and water ingress to the ship (see e.g. Kujala, 1991, Hänninen, 2005). This means that that from a safety point of view the acceptable amount of plastic deformation is difficult to determine. Economically we can increase the scantlings so that there will be no plastic deformation during the ship lifetime, which will cause high investment cost at the construction phase but no repair cost during the design life. Another possibility is to allow some local plasticity, which is expected to be repaired at specified nominal frequencies requiring smaller investments but higher

maintenance costs. The best compromise between these two extremes is searched in this paper and the procedure on how to identify such concept will be described.
Hence, direct calculations using the nonlinear Finite Element Method (FEM) will be carried out to assess the structural response of a stiffened side panel of a sample vessel. Furthermore, long-term load measurements will be utilized to dimension the stiffened panel for higher load levels and thereby to reduce the probable repair cost and to present the sensitivity.

***Typical ice induced loads and resulting hull damages***

Ice-induced loads are known to have a strong stochastic nature due to the stochastic nature of ice strength properties and the ship-ice interaction process. As ice is formed in nature, numerous variables affect the mechanical and physical properties of ice. In addition ship operations in ice can have various forms: independent navigation or navigation with icebreaker assistance e.g. in level ice, ice floes and ridged ice with various amounts of first year and multiyear ice features. Further, the possibility of the ship getting stuck in moving ice has to be included. The ice-breaking process has been successfully simulated lately in level ice with independent navigation (Su et al. 2011). Still, the physical process of ice breaking is not captured in all operative scenarios and ice conditions. The long-term full-scale measurements give the most reliable basis to evaluate the load level as a function of occurrence frequency (return period). Figure 1 shows an example the long-term loads measured on-board MV Kemira during a 7-year period from 1985-1991, including the rule-based design load, the maximum annual and lifetime loads. The transversely stiffened bulk carrier MS Kemira was built in 1980 to the highest Finnish-Swedish ice class 1A Super. In order to obtain these long-term loads MV Kemira was instrumented with shear strain gauges attached to the neutral axis of the frame where the difference between the two shear stresses on the same frame is proportional to the load on the frame between the gauges. The ship side-view and measurement locations are given in Figure 2, therefrom only the measurements from the mid ship section are utilized in this paper. The main particulars of MV Kemira are given in Table 1.

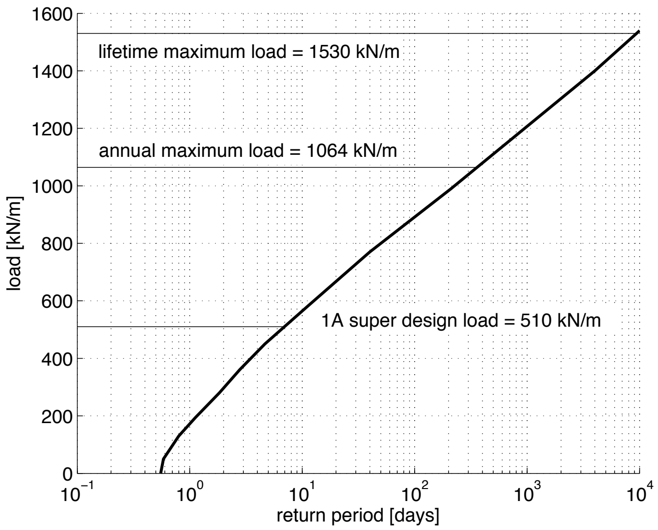


Figure 1. Long-term measured loads on a frame at the amidships of MV Kemira (Riska and Kämäräinen, 2011).

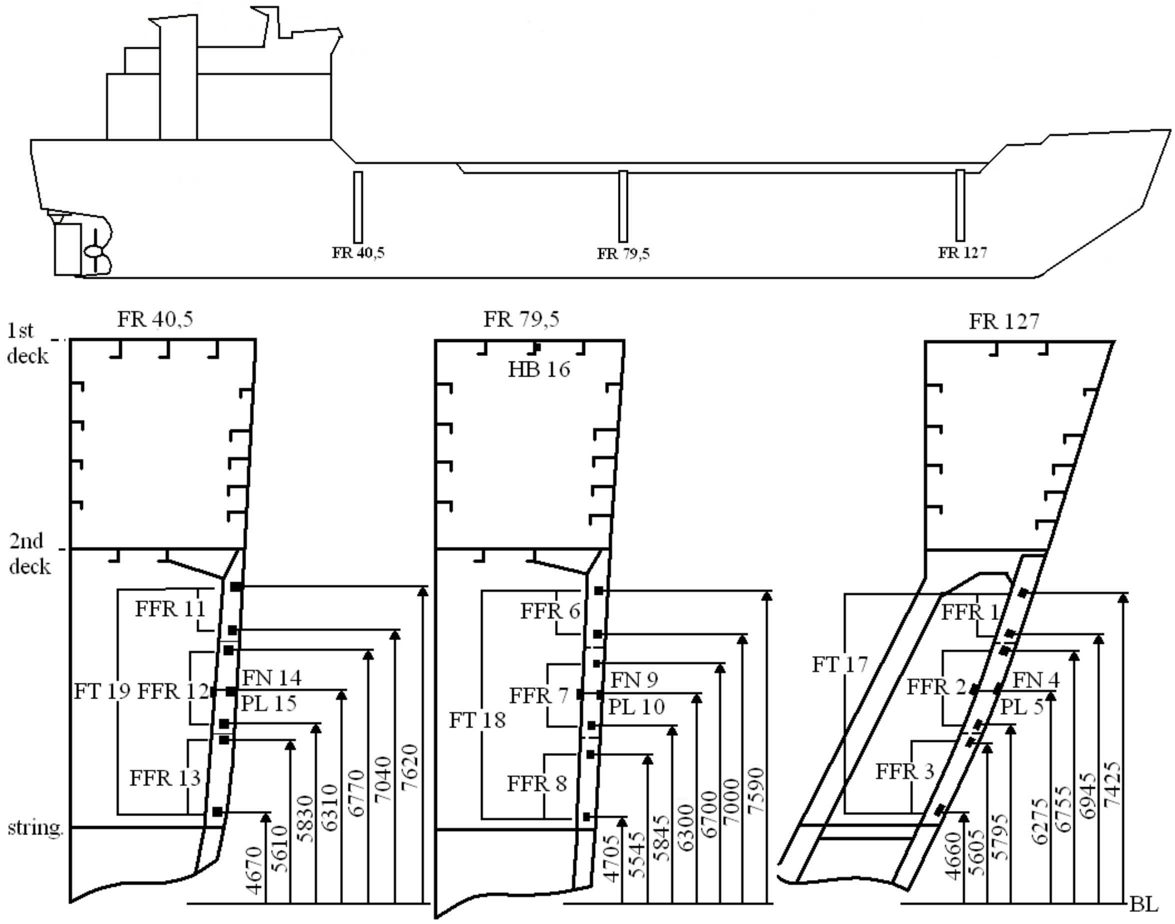


Figure 2. MV Kemira and the used instrumentation to obtain the data given in Figure 1 (Kujala, 1989).

Table 1. Main particulars of MV Kemira.

| | |
|---|---|
| $L_{bp}$ | 105 m |
| B | 17.5 m |
| T | 8.0 m |
| DWT | 8145 t |
| MCR | 3400 kW |
| $v_{ref}$ | 14 knots |

Figure 3 shows the ice-induced damage of a bulk carrier build in 1985 with the ice class 1A with 4693t DWT, a length of 91 m, a width of 16 m and a propulsion power of 2600 kW and an average draught at incident of 5.95 m. The damage extended over the full webframe spacing of 2.8 m and three stiffener spacings of 0.35 m resulting in a maximum deflection of 55mm deforming the 15.5 mm thick plating and longitudinal HP profiles of the dimension HP200x11.5. The webframes of the dimension 600x10 have not been deformed significantly. Typical for ice-induced damages is the permanent deflection in the centimetre range experienced by the plating between frames, whereas the transverse frames have somewhat minor deformations.

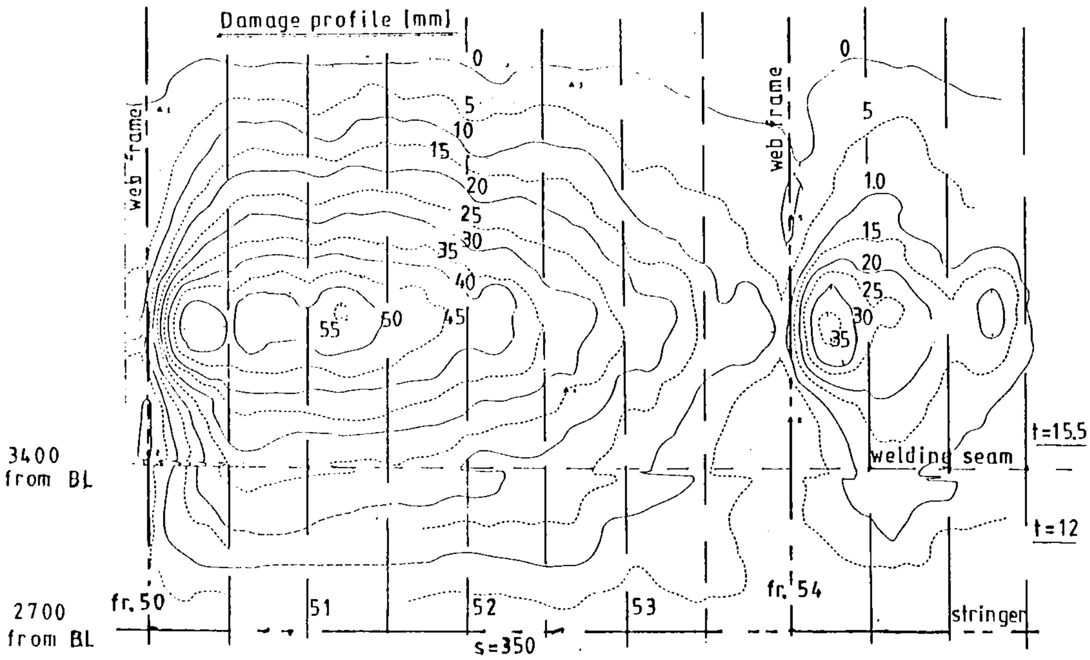

Figure 3. Observed ice-induced damage in a bulk carrier (Kujala, 1991).

**THE STRENGTH AND COST ASSESSMENT**

The case study structure is taken from MV Kemira, because long-term load measurements are available. The scantlings of the analysed panel are given in Table 2. These scantlings are obtained following the FSICR-design load for 1A super shown in Figure 1.

Table 2. MV Kemira side structure scantlings.

| | |
|---|---|
| Frame spacing, s | 0.35 m |
| Plate thickness | 16 mm |
| Profile type | HP240x11 |
| Length, L | 3.5 m |
| Width, S | 2.4 m |

In order to assess the influence of the load level on the production and repair cost the following cases are studied:

1) Rule-based load case: the scantlings of MV Kemira will be subjected to a rectangular pressure patch (i.e. 0.35 m in height spanning from webframe to webframe centrally between stringers in accordance with 1A super), which will then be increased following the long-term measurements given in Figure 1. As a result of the strength assessment, we will then obtain the permanently deflected volume to be repaired. Since the probability of the load is known, the overall probable annual repair cost can be obtained. Furthermore, the initial production cost is calculated.

2) A new structure will be designed for a higher ice-load. The stiffener, an assumed webframe and stringer spacing constant were left unchanged, and the plate thickness and frame section modulus were increased. The yield stress, i.e. first yield in the plating, was used as the limit state, which will results in no permanent deflection, i.e. local yielding, for the new design load level.

3) Step 2 will be repeated to cover the entire loading range to be expected over the vessels lifetime and the influence of the design load on the production and repair cost were investigated.

***The strength assessment model***

The explicit nonlinear Finite Element Method (FEM) solver LS-DYNA version 971R5 is used for the ice patch load simulations. The ANSYS parametric design language is used to build the finite element model for a nine-field strake model with variable structural dimensions; see Figure 4. For details on the parametric modelling see, for example, Ehlers et al. (2012). The three dimensional parametric model is supported at the boundary edges as shown in Figure 4. As a result, web frames and stringers surround the centre strake, thus resembling realistic boundary conditions for this panel. Consequently, the ice loading is applied to the structural elements of this centre panel as a pressure patch. The structure is modelled using four noded, quadrilateral Belytschko-Lin-Tsay shell elements with 5 integration points through their thickness. The finite element length is defined to result in three elements per stiffener spacing and height. This element size is well justified, because it sufficiently allows for non-linear structural deformations. Standard LS-DYNA hourglass control is used for the simulations; see Hallquist (2007). A bilinear material behaviour is implemented using material 3 of LS-DYNA (Hallquist, 2007); see Table 3.

Table 3. Bilinear material behaviour.

| | |
|---|---|
| Density | 7859 kg/m$^3$ |
| Young's modulus | 210 GPa |
| Poisson ratio | 0.3 |
| $\sigma_{yield}$ | 235 MPa |
| Tangent modulus | 1.14 GPa |

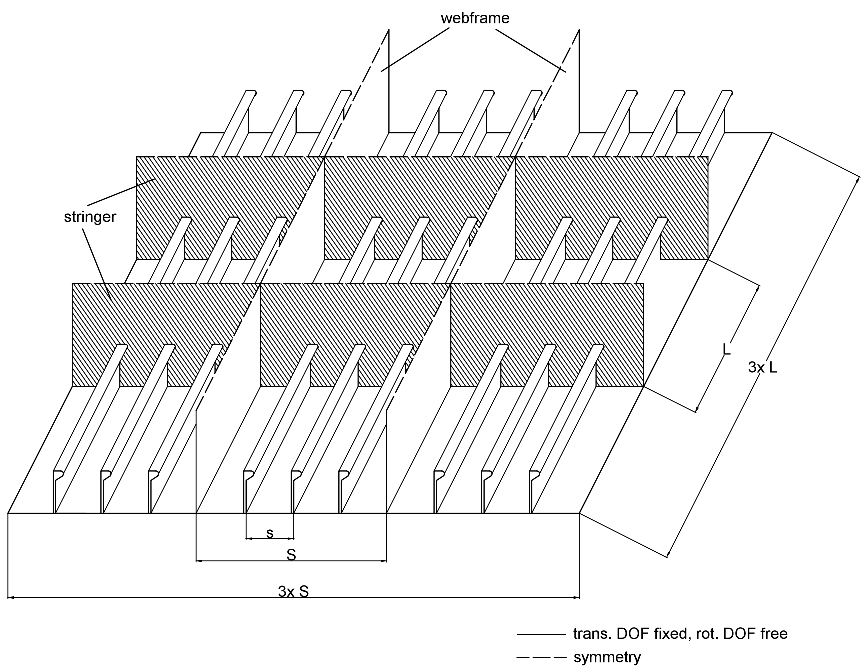


Figure 4. Panel overview and model extent for the finite element analysis.

***Production- and repair cost***

The steel structure production cost of each alternative is calculated with a cost module according to Rigo (2003). The cost is based on a simplified calculation of labour and material costs. The calculated cost is calibrated referring to the cost of a straight stiffened panel using unitary production costs of the yard. The production cost is calculated as a sum of three components:

$$\mathrm{Cost}_{\mathrm{total}} = \sum_{\mathrm{panel}} \left( \mathrm{cost}_{\mathrm{material}} + \mathrm{cost}_{\mathrm{consumables}} + \mathrm{cost}_{\mathrm{labour}} \right) \tag{1}$$

Material cost includes raw material cost for the plate and stiffeners. Cost of consumables consists of the costs from welding (energy, gas, electrodes and provision for equipment depreciation). Labour cost is based on the workload for surface preparation and welding.

The cost to repair the deformed side structure was also assessed. The steel replacement in a shipyard is assessed as a unit price of steel processed (USD/kg) for flat plates with correction factors for more laborious areas (Romanoff et al. 2007). Typical repair prices for per kg steel are given in Table 4 for quantities of 60kg to 20 tons. Laborious areas are subjected to certain correction coefficients ($C_{corr}$); see Table 5. These steel processing prices include material, workmanship, lighting and ventilation, but exclude staging, tank cleaning, testing the tanks and access work. Coating is also a separate job.

Table 4. Typical repair prices per kg normal steel.

| Country | USD/kg |
|---|---|
| China | 2.0 |
| Turkey | 3.6 |
| Greece | 10.8 |

Table 5. Correction coefficients for laborious repair areas.

| Laborious areas | $C_{corr}$ |
|---|---|
| Fore Peak, aft Peak and Ballast Tanks | 1.15 |
| Cargo Tanks and Engine rooms | 1.15 |
| Single curves plates | 1.15 |
| Holland profile | 1.25 |
| Oil and oily tanks | 1.20 |
| Plate thickness less then 10mm and more than 10mm | 1.15 |
| High Tensile Steel | 1.14 |

The repair cost for the different ice loads can be calculated for the obtained deformed ship side structure using the average price from Table 4 and the correction factors from Table 5 according to

$$C = \sum_{repair\_areas} C \cdot C_{corr} \tag{6}$$

The material is assumed to require repair if the resultant deformation is larger than the shell plate thickness. Furthermore, it is assumed that 20% of additional steel needs to be replaced during the repair. The final repair cost does not include the downtime and dry-docking, staging and coating costs.

## RESULTS AND DISCUSSION

The results of step 1 to 3 are presented in Table 6 and 7 rounded to the closes integer with case 1 being the current rule-based design load, see also Figure 1, and case 5 and 11 represent the maximum annual and lifetime load, respectively. Table 6 summarizes the repair cost to an annual probable level and presents the selected scantlings; while Table 7 presents the annual repair cost resulting from the damage, see Figure 5, caused by the load increase above the selected design point. Additionally, Figure 6 presents the maximum indentation caused by the load increased above the design point. Furthermore, in Table 7 the load refers to the long-term measurements presented in Figure 1, the scantling abbreviation are shown in Figure 4 while "t" denotes the plate thickness. The overall dimensions and the stiffener spacing are kept constant as shown in Table 2. The annual cost is evaluated assuming a ship lifetime of 25 years. Additionally, the objective of the newly designed structures was solely to reduce the annual production cost, which lead to a non-continuous increase in structural mass with an increase in load. The resulting combined annual production and repair cost as a function of the return period, respectively load-level, is presented in Figure 7, which clearly indicates their dependency. Most importantly, it can be seen that the structure designed according to a load level of 1064 kN/m to 1159 kN/m, which corresponds to a return period of 360 to 720 days, results in the lowest total annual cost. Thus representing an increase of at least 100% of the current design load level. Furthermore, the reason for the rapid decrease in total annual cost with increasing design load level arises from the dependency on the probability distribution presented in Figure 1. It becomes apparent that smaller loads are more probable to occur and consequently require more frequent repair. The same cost, respectively response, for the structures No 5 and 6 arises from the discrete steps in commonly available HP-profiles. Consequently, this suggests that a structure resulting in lower cost can be found in between these designs if the stiffener spacing or even webframe and stringer spacing is altered. Furthermore, the 1.6 times increase in structural mass could further be reduced by reducing the stiffener spacing, at a higher cost however. Nonetheless, since the total weight of the ice-strengthened structure is typically well below 10% of the total steel structure such increase in mass of the ice-strengthening will only slightly influence on the payload. Since, this study simply presents the possible gains for an existing structure through a comparison this is assumed to be negligible, because a newly designed vessel would give more degrees of freedom to compensate the eventually heavier hull structure. The current cost calculation can be seen as fairly reasonable, while the repair cost represents only the minimum cost to be encountered, because the significant loss due to the downtime of the vessel is not considered. Hence, the presented assessment can simply be extended if these cost details are known and thereby the structure resulting in lower over costs will tend to an even higher design load level.

A further justification of the need to consider the production and repair cost can be found when analysing the actually occurred ice-induced permanent deflection, i.e. the damage presented in Figure 3. In order to do so, the stiffened panel presented for this damage case is modelled analogously to Kemira's structure and at first subjected to the design pressure for its ice class 1A followed by a load identification to cause a permanent deflection of 55mm as measured. The resulting ratio between these two loads is found to be 2.6, which roughly corresponds to case No 7 in Table 6 and thus represents a valid case to be considered.

Table 6. Scantling, production and repair cost of the structures complying with the different design loads (* permanent deflection below plate thickness occurs for higher load levels and is thus not consider for repair).

| No | Load [kN/m] | T [days] | t [mm] | HP profile | Mass [kg] | Annual production cost [USD] | Annual probable repair cost [USD] |
|---|---|---|---|---|---|---|---|
| 1 | 510 | 7 | 16 | 240x11 | 1707 | 49 | 604 |
| 2 | 622 | 15 | 16 | 260x11 | 1780 | 51 | 192 |
| 3 | 727 | 30 | 17 | 280x11 | 1942 | 54 | 104 |
| 4 | 969 | 180 | 20 | 300x11 | 2218 | 71 | 28 |
| 5 | 1064 | 360 | 24 | 320x13 | 2687 | 75 | 13 |
| 6 | 1159 | 720 | 24 | 320x13 | 2687 | 75 | 13 |
| 7 | 1286 | 1800 | 19 | 340x12 | 2385 | 145 | 0* |
| 8 | 1382 | 3600 | 23 | 340x12 | 2649 | 152 | 0* |
| 9 | 1445 | 5400 | 23 | 340x12 | 2649 | 152 | 0* |
| 10 | 1489 | 7200 | 24 | 340x12 | 2715 | 153 | 0* |
| 11 | 1530 | 9000 | 24 | 340x12 | 2715 | 153 | 0 |

Table 7. Annual repair cost resulting from the probable load above the selected design point (DL – Design Load)

| No | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | DL | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | DL | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 7200 | 0 | DL | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 14415 | 9071 | 1801 | DL | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 18770 | 15791 | 9983 | 0 | DL | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 45257 | 23008 | 17301 | 1578 | 0 | DL | 0 | 0 | 0 | 0 | 0 |
| 7 | 117448 | 30882 | 27647 | 12985 | 511 | 511 | DL | 0 | 0 | 0 | 0 |
| 8 | 136796 | 43238 | 33769 | 20947 | 10327 | 10327 | 0 | DL | 0 | 0 | 0 |
| 9 | 146497 | 64477 | 37375 | 27264 | 17710 | 17710 | 0 | 0 | DL | 0 | 0 |
| 10 | 151868 | 90425 | 40082 | 31158 | 22890 | 22890 | 0 | 0 | 0 | DL | 0 |
| 11 | 156125 | 105798 | 44489 | 34366 | 29034 | 29034 | 0 | 0 | 0 | 0 | DL |

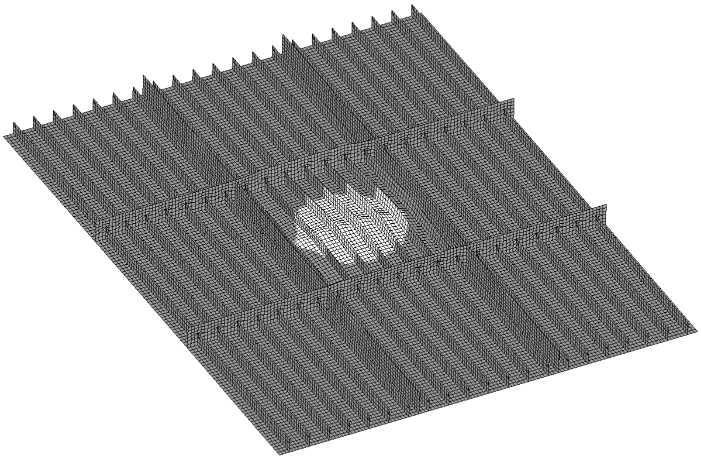

Figure 5. Resulting panel deformations with highlighted area deformed above the repair limit, i.e. plate thickness (displacement scale factor is 5).

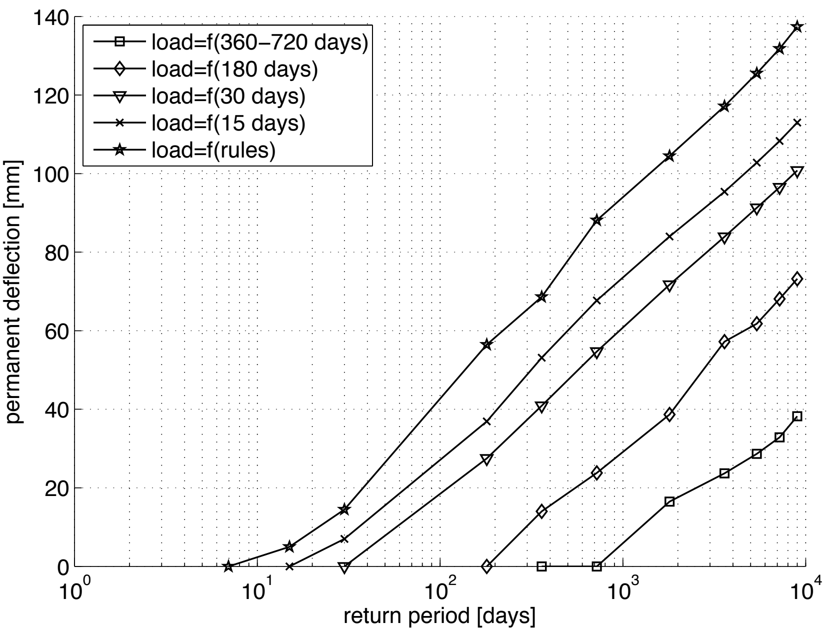


Figure 6. Maximum plate indentation resulting from the load increase above the design point.

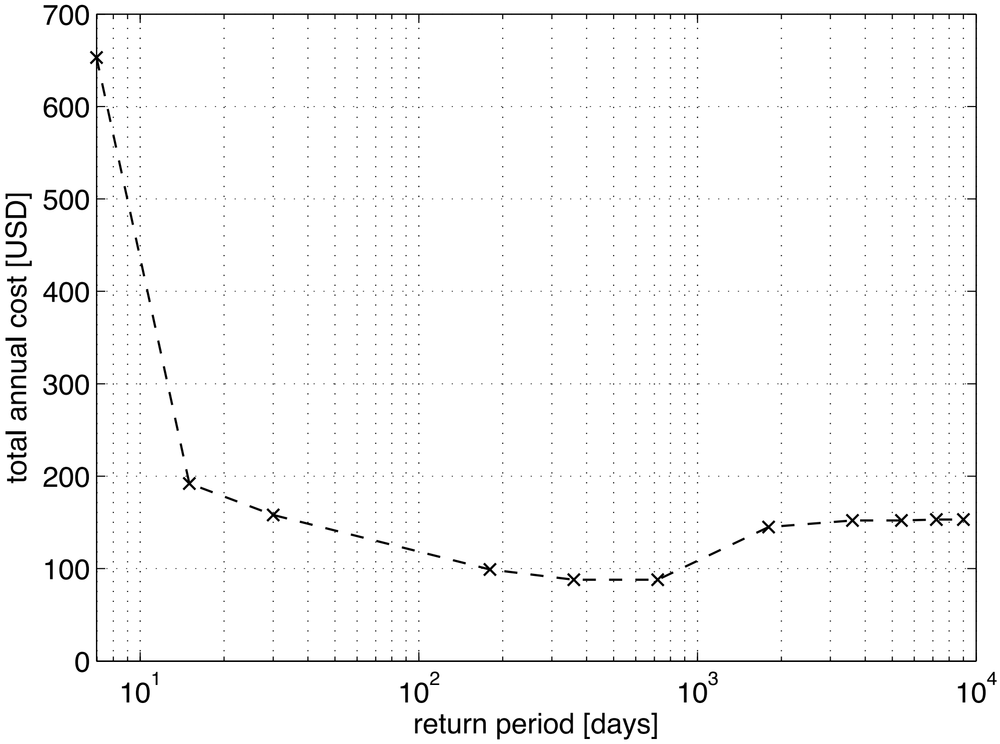


Figure 7. Combined annual production and repair cost as a function of the return period.

**SUMMARY**

This paper presented a study of design load level for ice-strengthened structures by means of production and repair cost. The repair cost has been assessed following long-term measurements and their probability of occurrence and further justified by a comparison to a typical and measured ice-induced damage. This economic assessment of the design load concludes that the load level needs to be increased to a higher level then suggested by the FSICR today. The presented examples suggest an increase in design load by a factor of 2. This will however require further analysis with different vessels and ice classes. Hence, the future work will define an optimization-based procedure to identify the optimal structure in view of repair cost, design load and point as well as production cost for the vessel in question.

**REFERENCES**

Ehlers, S. 2012. A particle swarm algorithm-based optimization for high-strength steel structures. J of Ship Production and Design, 28(1): 1–9.

Hallquist, J.O. 2007. LS-DYNA. Keyword User's Manual, Version 971, Livermore Software Technology Corporation.

Hänninen, S. 2005. Incidents and Accidents in Winter Navigation in the Baltic Sea, Winter 2002-2003. Winter Navigation Research Board, Research Report No. 54, Helsinki, p. 39.

Kaldasaun, J. and Kujala, P., 2011. Risk-Based Approach for Structural Design of Ice-Strengthened Vessels Navigating in the Baltic Sea. Proceedings of the 21st International Conference on Port and Ocean Engineering under Arctic Conditions, July 10-14, Montréal, Canada.

Kujala, P. 1991. Damage statistics of ice-strengthened ships in the Baltic Sea 1984-1987. Winter Navigation Research Board. Report. No. 50. 61 p. + app. 5 p.
Kujala, P. 1989. Long term ice load measurements onboard chemical tanker Kemira during winters 1985 to 1988. Helsinki. Winter Navigation Research Board. Report. No. 47. 55 p. + app. 139 p.

Muhonen, A., 1992. Ice Load Measurements on Board the MS Kemira, Winter 1991. Otaniemi. Helsinki University of Technology, Laboratory of Naval Architecture and Marine Engineering, Report M-121. ISBN 951-22-1173-4.

Rigo, P. 2003. An Integrated Software for Scantling Optimization and Least Production Cost. Ship Technology Research 50: 126-141.

Riska, K. 2007: Application of the SAFEICE Project Results in Developing the Finnish Swedish Ice Class Rules. Deliverable D7-3 from the SAFEICE project. In Kujala, ed. 27 p.

Riska, K. and Kämäräinen, J., 2011. A Review of Ice Loading and the Evolution of the Finnish-Swedish Ice Class Rules. SNAME Transactions, to be published.

Romanoff et al. 2007. Catalogue of the Selected Methods to Solve the Structural, Production and Operation Issues Affecting Design of 3 Application Cases. EU IMPROVE project Deliverable 2.6.

Su, B., Riska, K., Moan, T., 2011. Numerical simulation of local ice loads in uniform and randomly varying ice conditions. Cold Regions Science and Technology, 65: 145–59.