Collision and grounding in Arctic conditions

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Ice belt weight reduction of ships operating in ice floe infested waters with the direct calculation method

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ABSTRACT: The IACS (International Association of Classification Societies) Polar Code (PC rules) provides design rules for ships operating in ice floe infested waters. Such a design has a Polar Class (PC) designation ranging from PC7 to PC1 in order of more severe ice loads. The PC rules prescribe the shell plating and local framing with semi-empirical equations, and the load-carrying stringers and web frames by direct calculation with linear or Non-Linear (NL) Finite Element Analysis (FEA). For ships occasionally operating in partial ice-covered waters, following the PC rules, the added weight for ice protection may render it inefficient in other operational conditions. A direct approach for all the scantlings, balancing the actual loads and integrity requirements for limited use in ice floe infested waters may be beneficial for such ships. In this paper PC rules and full NL FEA methodologies have been applied to the intermediate bow region of a reference PC6 frigate. A structural mass reduction of up to 11% has been obtained with respect to a PC rules design. Multiple ice impacts at the same location have been considered for the reduced design to assess the maximum hull deformation to be expected for the design when operating in ice floe infested waters. The calculation method, numerical results and structural modifications are presented and discussed.

1 INTRODUCTION

1.1 *Context and background*

One of the challenges for the future design of naval vessels operating in partially ice floe infested waters, is to reduce the structural mass of such ships while withstanding ice floe impacts on the hull, especially when such operations are limited related to the total design life. The design loads that such a vessel needs to withstand are prescribed by rules like the International Association of Classification Societies (IACS) Polar Code (PC rules) (IACS 2019).

The underlying issue is that the design and operational profile of naval ships, is different from the common ice breaker shaped ships for which the PC rules are developed. This especially holds true for naval ships that only incidentally expect operations in ice floe infested waters and also require performance in conditions without ice.

The PC rules (IACS 2019) prescribe the shell plating and local framing with semi-empirical equations, and the load-carrying stringers and web frames by direct calculation with linear or Non-Linear (NL) FEM. The use of two different methods for the different structural elements may result in an unbalanced structural design, and the use of direct calculations for all scantlings may result in a more balanced and lighter design. It is of interest to compare the added mass of reinforcements from PC rules prescribed linear and non-linear direct calculation methods, and two non-linear direct calculation approaches.

The linear and non-linear direct calculation methods are according to the PC rules and are applied to a Polar Class (PC) 7 and 6 frigate design and are referred to as the PC rules approaches.

An improved PC NL FEA approach is used which is based on the PC rules for shell plating and ice framing, and NL DNV rules (DNV 2022) for the web frame and stringers. This approach uses the same static ice load patch as prescribed by the NL FEA PC rules. This method is applied to a PC7 and PC6 frigate design. Optimisation is done manually only. Method comparison is the main objective.

The DDePS-2a (Direct Design for Polar Ships scenario 2a) NL FEA method uses the direct calculation methodology used in (Bobeldijk et al. 2021). The approach is based on the DDePS-2a analytical ice load model for a shoulder glancing ice floe collision scenario, described in (Dolny 2017, Dolny 2018), which is converted to a load patch for NL

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FEA applications. The methodology uses a sliding ice load as a sliding load may cause significantly more damage than a static load, as shown in (Quinton et al. 2010, Quinton et al. 2012). This method is applied to a PC6 frigate design. Also for this method the optimisation is done manually only by engineering judgement.

Comparing the four different methods provides insight into the added value of direct calculations, and cross-verification and caveats of the methods used.

Direct calculation methods as presented in this paper may be an useful tool within a risk-based framework, such as the one presented by (Bergström et al. 2022).

When occasionally sailing through ice floe infested waters with a non-ice strengthened ship, a risk based approach may help to select scenarios and consider the acceptability of the effects. Low and high energy impacts and impacts at various positions along the ship are associated with a likelihood of occurrence, and an associated damage. The latter is then a consequence that in the worst case leads to loss of watertight integrity, but more often only in minor structural deformation. Direct calculation methods as presented in this paper, with appropriate FE models and criteria, allow the designer to mark the scenarios in a graph similar to the one shown in Figure 1.

For non-ice strengthened ships sailing in ice floe infested waters, multi impact scenarios may become important. Such a ship is not designed for high ice impact loads and may experience increasing deformation due to subsequent impacts than an ice-strengthened ship. It is therefore of interest to also look into multi-impact scenarios.

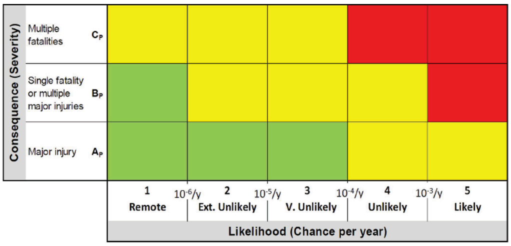

Figure 1. Risk matrix as used in formal safety assessment (IMO 2018).

1.2 *Research questions*

The research questions addressed in this paper are:

- Which weight reduction for a PC6 and/or PC7 design can be obtained by using direct calculation methods, and what is the effect of multiple ice floe impacts on such a design?
- To what extent do the improved PC NL FEA approach and the DDePS-2a NL FEA method yield different results?
- What is effect of multi-impact on the PC6 design in case small plastic deformations are allowed?

2 METHODOLOGY

2.1 *PC rules designs*

For the initial PC6 design, shell plating and local framing are designed according to the empirically based method presented by the PC rules. The design load in the PC rules correspond to a rare event that produces a high load. In fact, the approach in the PC rules is that the structure is allowed to yield under the applied design load with a substantial reserve against collapse and rupture.

For the design of shell plating and local framing a set of equations is provided by the PC rules. The PC rules require the strength of load carrying stringers and web frames forming part of a grillage system to be assessed using either a linear or non-linear direct calculation method. These structural elements are in this paper referred to as primary structures. The PC rules do not allow direct calculations for prescribing the shell plating and local framing.

Traditionally, ships with ice strengthening are designed with a transverse framing system containing additional ice framing at half of the frame spacing. The ice framing is designed to withstand ice loads which increase from PC7 to PC1. However, the traditional design can be optimised for the side and bottom structure. To reduce the amount of added steel and choosing a proper framing system, a single panel for PC7 and PC6 requirements has been considered. Transverse and longitudinal framing systems are evaluated on the bottom and side structure according to the PC rules.

For this approach the integrated DNV software Nauticus Hull has been used where the PC rules, minimum scantling and hull girder have been verified in accordance with the DNV ship rules. Both frame spacing and framing system have been studied for the bottom and side of ship structure. The implementation of the stringer between transverses is verified with PC rules and regulations, and the impact of this modification on the weight is evaluated.

This approach results in a PC7 and PC6 compliant design using:

1. The PC rules for linear direct calculations;
2. The PC rules for non-linear direct calculations.

2.2 *Improved PC NL FEA approach*

The PC rules require the scantlings of primary structures to be assessed using either a linear or non-linear direct calculation method. Linear methods only consider the elastic regime of the steel material, meaning that no permanent deformation will occur.

Non-linear methods also consider the plastic region, meaning that permanent plastic deformation of the structure may occur.

Linear analysis in this context is problematic as the local structures and shell plating are designed to a plastic limit state (utilising the analytical equations in the rules), while the primary structures in a polar frigate are designed to an elastic limit state. The difference in limit states may result in an imbalanced structure where the primary structures are overly strong compared to the local structures of the polar frigate.

For non-linear analysis the DNV classification society currently presents guidelines for load carrying stringers and web frames for different load cases (DNV 2022). The primary structures have been evaluated by linear and non-linear FE analysis. Existing rule requirements for non-linear analysis are high level in nature and isolate the primary structure design from local framing and shell plating. Just as for the linear analysis this may result in an unbalanced design.

The side shell structure of polar frigates consists largely of shell plating. Reducing the primary structural elements such as web frames and stringers may not have extensive impact on the total steel mass. As NL FEA is both time consuming and complex, optimisation using this type of analysis to obtain a minor modification in steel weight is not beneficial.

Instead it is proposed to use the same design concept and limit state for both the primary and local structures. The approach uses direct calculations to design the primary structure, shell plating and ice framing by NL FEA. It is desirable that under overload the structure fails gradually. A moderate overloading may cause permanent deformation but does not lead to structural failure, such as rupture of the shell plating or collapse of the structure.

The current rule requirements for non-linear analysis are high level and not straightforward to apply. It requires a complex combination of PC and ship rules, as well as the non-linear guidance. (Valtonen et al. 2020) introduced a more robust method and the presented approach is used here in a similar way. The methodology proposed here is simple to apply and ensures a proper structural design hierarchy, see Figure 2. The initial design phase is the conventional design process, whereas the follow-up phases ensure the optimisation using non-linear direct methods. This approach is applied to a PC7 and PC6 frigate design. The proposed method is outlined in Figure 2.

2.3 *DDePS-2a NL FEA methodology*

This approach uses the direct calculation methodology described in (Bobeldijk et al. 2021). This methodology is based on the DDePS-2a engineering model (Dolny 2018) to determine the contact area and nominal pressure of the ice load on the hull of the ship, and converts this load to a representation suitable for

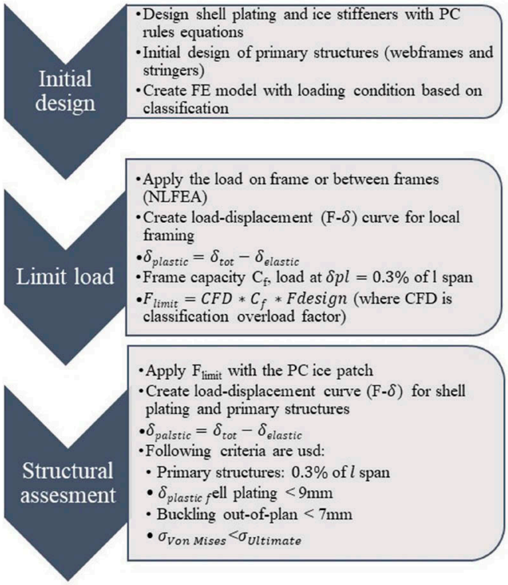

Figure 2. Proposed method for non-linear FEA assisted design of polar ships.

NL FEA. The DDePS-2a is based on a heavy shoulder glancing scenario with a finite ice floe.

The ice load is then applied at different locations along the hull and FEA simulations are performed.

The results of the simulations are then compared to defined acceptance criteria, and conclusions and recommendations are made.

For the DDePS-2a NL FEA method two input loads are considered: a representative medium first-year ice load as defined in (Bobeldijk et al. 2021) and the load as prescribed by the PC rules direct calculation for a PC6 intermediate bow section. For both loads, a non-moving (stationary) and moving (sliding) load are considered to investigate the impact of a stationary load assumption.

3 FEA MODELS

3.1 *PC rules design*

The implicit solver of FEMAP 2022.2 is used for the simulations. The FEA model is the same as used for the improved PC NL FEA approach.

3.2 *Improved PC NL FEA approach*

The implicit solver of FEMAP 2022.2 is used for the simulations.

The model extent and parameters are based on the DNV rules for direct calculations (DNV 2020). In the longitudinal direction, the model extends between two transverse bulkheads, which provide a rigid support of the side shell structure.

The model considers three web frame spacings in longitudinal direction, where one web frame spacing is 1500 mm. The modelling region extends to both sides of the web frame where the ice patch will be applied. In the vertical direction, the model extends from the bottom to the deck above the ice belt. The model domain is illustrated in Figure 3.

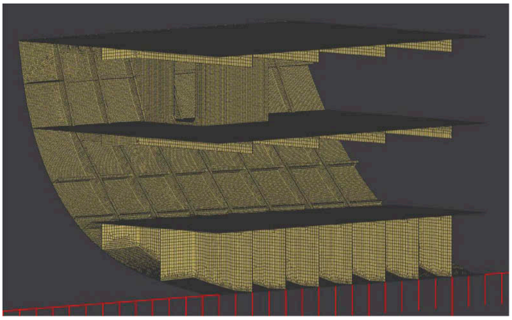

Figure 3. Bow intermediate section model for calculation.

The model uses shell elements for the plates and stiffeners. In the region of impact quadrilateral elements have been used pre-dominantly.

Bulb profiles are modelled as equivalent L-profiles. All smaller openings such as cut-outs, lighting holes in deck beams and floors, which are not in the vicinity of the hotspot area are omitted, as well as the smaller structural elements such as lugs and tripping brackets.

The element size is in accordance to (DNV 2020). The minimum element size for the web, shell plating and ice stringers is 50 mm. The mesh of the model is shown in Figure 3.

The material model is according to the S355 steel specified in Section 4.6 of (DNV-GL 2016).

The transverse direction of the model is constraint at the centreline and the side shell. All degrees of freedom at the centreline are fixed, the forward and aft ends of the deck and shell are fixed in the longitudinal direction and fixed in rotation about the transverse and vertical axes.

The ice load and patch according to the PC rules (IACS 2019) has been applied to various impact locations specified in Section 6, Table 2 of (DNV 2020). A summary of the different load cases is shown in Figure 4.

The acceptance criteria are defined in Figure 1 and are based on the DNV guideline for direct calculation for polar ships noted in (DNV 2022).

3.3 *DDePS-2a NL FEA methodology*

The simulations are performed with the explicit FEA solver LS-Dyna version R12.

Two structural models are considered: one is based on the PC6 design arising from the PC rules with linear direct calculation and the other is a modified lighter weight version of that design which is expected, by engineering judgement, to be on the edge of acceptance according to the presented method. The former is referred to as the 'PC6 design' and the latter as the 'modified PC6 design'. The modifications are summarised in Table 1. Modifications are performed based on calculation results and engineering judgement and may not be the optimised structural arrangement. Stiffener and frame spacing have not been altered with respect to the original design.

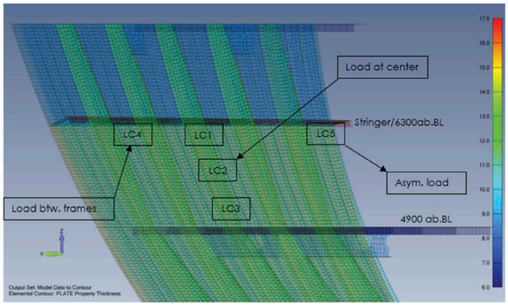

Figure 4. Patch locations (load cases). The contour plot shows the plate thickness for a PC7 design.

The region between deck 3 and 5, and bulkheads 94 and 112 is modelled. Several simplifications have been made:

- The hull is straight both in the vertical and longitudinal direction;
- Below deck 4 the ice stringer is attached to the web frame by a cut-out with lug plate. This has been modelled as continuous web;
- Other bulkheads and decks have not been modelled explicitly but are modelled with boundary conditions.

Table 1. Comparison between the PC6 and modified PC6 design for the intermediate bow section. All values are in mm.

Description	PC6	PC6 mod.
Thickness of brackets at connection transverses to deck	6	10
Transverses	HP220x12	HP180x10
Ice stringer	300x90x12x17	250x80x10x15
Shell thickness of the ice belt (between ice stringers)	15.5	14
Web frames	T300x14-100x16	T250x12-100x14

The model uses Belytschko-Tsay shell elements with five integration points through the thickness. Mainly quad elements have been used with triangular elements where unavoidable.

Bulb flat profiles have been modelled with shells for the web and a beam element for the bulb. The bulb has been modelled with five integration points using the *INTEGRATION_BEAM keyword.

A distinction is made between a fine and a coarse region. In the fine region a nominal element size of 20 mm is used and in the coarse region a nominal element size of 30 mm. The mesh is illustrated in Figure 5.

Fixed (clamped) boundary conditions are imposed on the free edges of the model.

The design consists of AH36 steel. The hardening behaviour model for EH36 used in (Bobeldijk et al. 2021) has been used. (DNV-GL 2016) prescribes a different plasticity curve for S355 for non-linear finite element analysis depending on the thickness. This material model is used for the improved PC NL FEA approach. A comparison between the material curves is provided in Figure 6. The EH36 material model is representative for the materials curves up to 16 mm and from 16 to 40 mm thickness and is used further.

For post-processing purposes the model is rotated about the x-axis such that the y-axis is aligned with the normal of the side shell. The purpose is to obtain and visualize the normal shell displacement during post-processing in a straightforward manner. To obtain the out-of-plane deck displacement, the absolute of the displacement in the yz-plane is used.

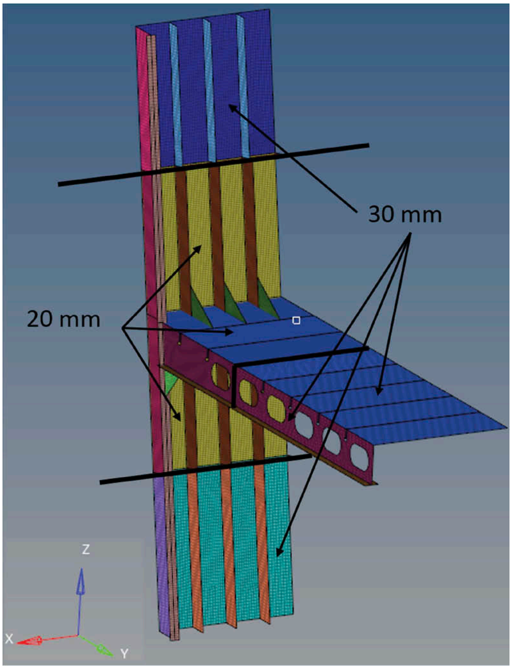

Figure 5. Nominal element sizes in the PC6 and modified PC6 models for the DDePS-2a NL FEA methodology.

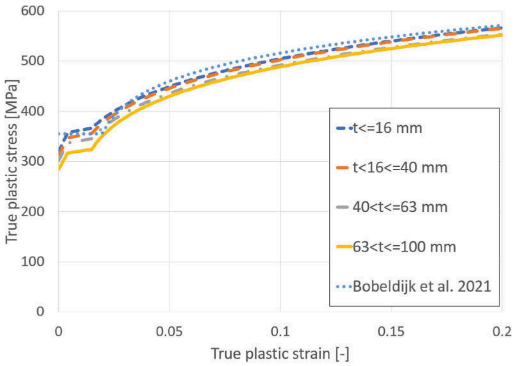

Figure 6. Comparison between the DNV-GL 2016 S355 plasticity curves for non-linear finite element analysis and the EH36 model from Bobeldijk et al. 2021.

The PC rules direct calculations consider a static patch. With the NL FEA direct calculation methodology, a static or dynamic (moving) load patch can be considered. It is of interest to compare results for both approaches.

The DDePS-2a model requires several ice parameters for determining the ice load: ice floe dimensions (L x B), ice floe thickness (h_{ice}), ice density (ρ_{ice}), flexural strength (σ_f), nominal crushing strength (P_0), nominal crushing strength exponent (ex) and ice wedge angle (φ). Other required inputs are the sailing speed (Vs), impact location and ship characteristics.

Two sets of ice parameters are considered in this paper. One set is the ice parameters used in (Bobeldijk et al. 2021) representing a medium first-year ice floe impact load and will be referred to as "patch 1". The other set of ice parameters are fitted such that the same load patch characteristics are obtained (average pressure and load patch dimensions) as prescribed by the PC rules for PC6 and is referred to as "patch 2". Note that a sailing speed of 5 m/s has been used for both patches.

The ice floe properties and sailing speed inputs for the load patches are provided in Table 2. The resulting ice load patch characteristics are given in Table 3, where P_{avg}^{end} is the average pressure at the end of the contact, w_{end} is the width of the load patch at the end of the contact, h_{end} is the height of the load patch at the end of the contact and F_{max} is the maximum normal force, which is obtained at the end of the contact.

Three impact locations are considered (see Figure 7):

1. Impact on the Ice Stringer (IS) above the deck;
2. Impact on the Upper WaterLine (UWL);
3. Impact on the Lower WaterLine (LWL).

The longitudinal impact location depends on the type of patch: stationary or moving. The location is chosen such that the location at which the contact is released (and the force is at its highest) is the same for all simulations. This is illustrated in Figure 8.

Table 2. Ice floe properties and sailing speed inputs for "patch 1" and "patch 2".

Input	Unit	Patch 1	Patch 2
L x B	m x m	100 x 100	80 x 80
h_{ice}	m	0.8	1.4
ρ_{ice}	kg/m^3	920	920
σ_f	MPa	0.8	0.8
P_0	MPa	2.0	1.2
ex	-	-0.1	-0.1
φ	°	120	164
V_s	m/s	5.0	5.0

Table 3. Load patch characteristics for load "patch 1" and "patch 2".

Characteristic	Unit	Patch 1	Patch 2
P_{avg}^{end}	MPa	4.2	2.3
w^{end}	m	0.45	1.49
h^{end}	M	0.76	0.59
F_{max}	MN	1.4	2.0

Figure 7. Illustration of impact locations for the stationary patch. Top: IS, middle: UWL, and lower: LWL. Deck has been blanked.

To assess whether the design is sufficient to withstand the ice loads, acceptance criteria are defined. Three acceptance criteria are based on rules and guidelines of (DNV 2022):

– **Maximum shell displacement**: the residual y-displacement (out-of-plane) of the shell at the end of the analysis may not exceed 9 mm;
– **Maximum deck displacement**: the residual yz-displacement (out-of-plane) of the deck and its stiffening components at the end of the analysis may not exceed 8 mm;
– **Maximum plastic strain:** the maximum plastic strain may not exceed 5%.

In addition, a fourth criterion is used, which is taken from (Bobeldijk et al. 2021):

– **Stiffener rotation:** the rotation of the stiffener at the end of the analysis may not exceed an angle of 4.7°.

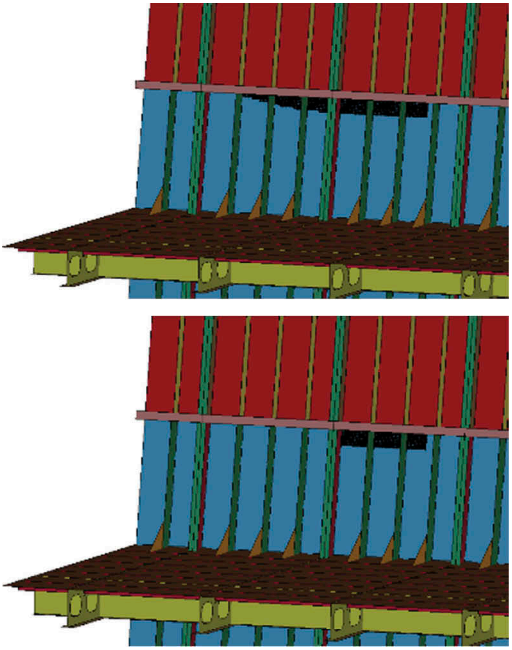

Figure 8. Illustration of a moving (top) and stationary (bottom) load patch for impact at the ice stiffener.

3.4 *Multi-impact*

To assess the effect of multi-impact, the PC6 design model of the DDePS-2a NL FEA methodology is used.

The moving "patch 1" ice load is applied at the same location five times consecutively for the PC6 design. The consecutive impacts are simulated in a single simulation with a 0.5 s interval between the impacts.

A structural damping coefficient of 0.05 has been used to reduce the effect of kinetic deformations due to sudden release of the load at the time that the contact ends.

4 RESULTS

For the PC rules designs and improved NL FEA PC approach, the total reinforcement mass is used for comparison.

Results for the DDePS-2a NL FEA methodology and multi-impact analyses are compared based on usage factors. A usage factor is the ratio between the value and the limit of the criterion. The results for various designs and criteria are easily compared in this way.

For the discussion of the results, the mass of the different designs are compared with a consistent method.

4.1 *PC rules designs and improved NL FEA PC approach*

In Table 4, the total reinforcement mass of the PC rules design (PC rules with linear and non-linear direct calculation) and the improved NL FEA PC approach are shown for PC7 and PC6 frigate designs. The total reinforcement mass is the mass that is added to a non-ice strengthened ship to reach the set PC level. The reinforcement mass is determined for the entire ship by using the analysis results in combination with empirical mass estimation rules.

As can be seen from the results, the mass reduction between the PC rules linear and non-linear direct calculations is relatively small. This is because the steel plating forms most of the steel mass whereas the direct calculation approach only influences the primary structure. The mass reduction of added reinforcement by using the improved direct calculation approach is up to 35% for the PC7 design compared to the linear direct calculation design.

Table 4. Total reinforcement mass in tonnes for PC7 and PC6 designs obtained from the PC rules + linear direct calculation, PC rules + non-linear direct calculation, and improved NL FEA PC approach methods.

Method	PC7	PC6
PC rules + linear	166	205
PC rules + non-linear	159	197
Improved NL FEA PC approach	108	141

4.2 *DDePS-2a NL FEA methodology*

The usage factors of the acceptance criteria for the stationary patches at different impact locations for the PC6 design are shown in Figure 9. The usage factors for the moving patches are given in Figure 10.

The moving ice load patch causes larger local deformations than the stationary load. This is especially apparent for “patch 1”.

The PC6 design does not exceed any of the usage factors for “patch 2”, the ice load prescribed for direct calculations of PC6 design. From Figures 9 and 10 it can be seen that the usage factor for the maximum deck displacement is 0 for both the stationary and moving patch analyses. The chosen patches do not result in deck deformation.

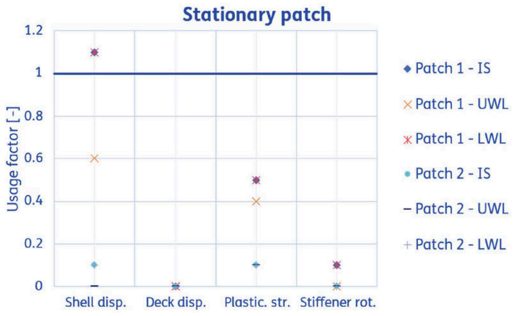

Figure 9. Acceptance criteria results for the stationary load patch analyses.

For “patch 1”, the shell displacement criterion is exceeded for both the stationary and moving load patch, with a maximum of 1.4 for the moving ice load for the shell displacement criterion.

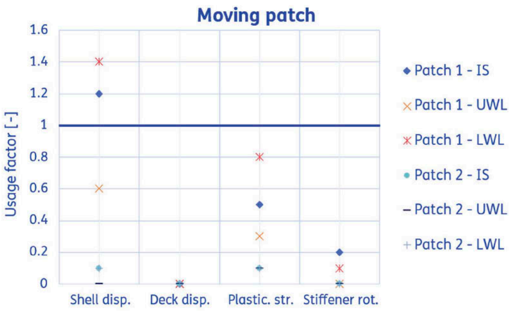

Figure 10. Acceptance criteria results for the moving load patch analyses.

The usage factors for the stationary and moving patches for the modified PC6 design are given in Figures 11 and 12. For the modified design the same tendencies are observed as for the PC6 design analyses:

- The moving load patch is more severe than the stationary patch;
- The representative medium first-year ice patch (“patch 1”) produces the most severe deformations of the structure;
- For (stationary) “patch 2”, none of the acceptance criteria are exceeded.

Stationary “patch 2” is selected as the benchmark requirement, which is reasonable considering that the original PC6 design also exceeds the “patch 1” load. With this, the modified design meets the load requirement. The mass of the ice belt region of the modified design is reduced by 11% compared to the original design. The mass difference is calculated based on the shell scantlings and the deck brackets of the original and modified FEA models, and is different from the mass presented in Table 4.

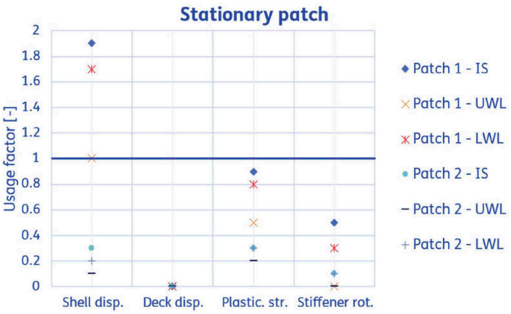

Figure 11. Acceptance criteria results for the stationary load patch analyses.

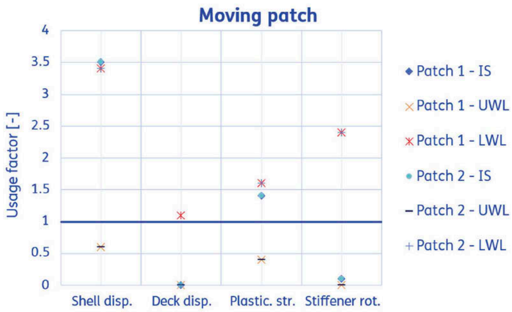

Figure 12. Acceptance criteria results for the moving load patch analyses.

4.3 *Multi-impact*

The acceptance criteria after each impact for the IS, UWL and LWL load scenarios are plotted in Figures 13, 14 and 15.

For each load scenario it can be seen that the usage factors increase after subsequent loading. The increase reduces per subsequent impact.

For the LWL scenario, the plastic strain acceptance criterion is not exceeded upon the first two impacts but exceeds this criterion afterwards.

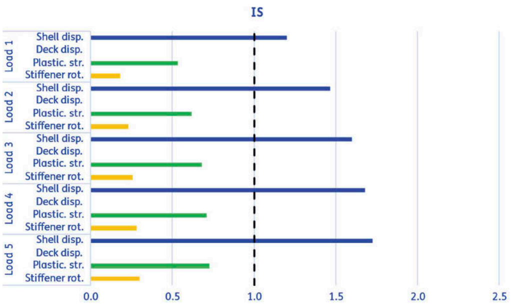

Figure 13. Acceptance criteria after each impact for impact on the Ice Stringer (IS) scenario.

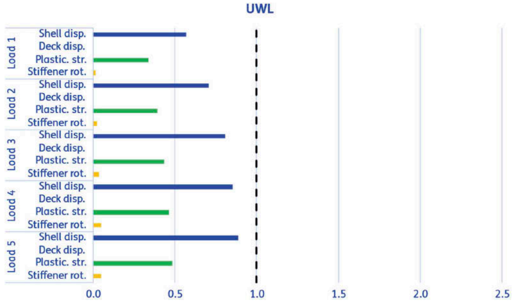

Figure 14. Acceptance criteria after each impact for impact at the Upper WaterLine (UWL) scenario.

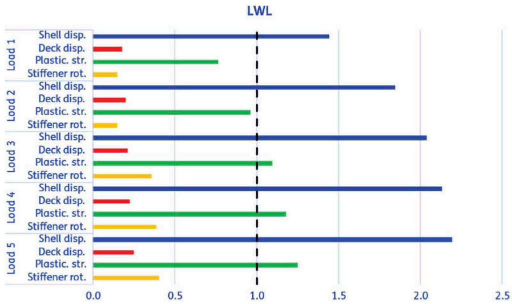

Figure 15. Acceptance criteria after each impact for impact at the Lower WaterLine (LWL) scenario.

5 DISCUSSION

5.1 *Comparison of methods*

Four different methods have been applied to the bow intermediate region of a PC6 frigate design. The base structure follows from the PC rules with a linear direction calculation approach. The design modifications that follow from the PC rules with non-linear direct calculation, improved PC NL FEA approach and DDePS-2a NL FEA method are summarised in Tables 5 and 6.

Comparing the mass of the different designs is not trivial. For the PC rules approaches, the reinforcement mass has been calculated for the entire ship based on the results of Tables 5 and 6 and empirical relations. For the DDePS-2a NL FEA approach this has not be done.

To compare the mass of the different designs, the model used for the DDePS-2a NL FEA has been used to incorporate all of the different design changes. The resulting mass of the outer shell (including all the scantlings) and the deck brackets are compared. The difference in mass is summarised in Table 7.

The PC rules designs are more conservative due to only allowing the direct calculations for the stringers and web frames. The improved NL FEA PC approach shows that a larger reduction can be

Table 5. Scantling designs for the intermediate bow area following from the different design methods discussed in this paper that show acceptable performance against a PC6 level ice load. All values are in mm.

Method	Thickness of brackets	Transverses	Ice stringer
PC rules + linear	6.0	HP220x12	300x90x12x17
PC rules + non-linear	6.0	HP220x12	300x90x10x17
Improved NL FEA PC	6.0	HP220x12	300x100x9x16
DDePS-2a NL FEA	10.0	HP180x10	250x80x10x15

Table 6. Continuation of Table 5. All values are in mm.

Method	Shell thickness of the ice belt	Web frames
PC rules + linear	6.0	HP220x12
PC rules + non-linear	6.0	HP220x12
Improved NL FEA PC	6.0	HP220x12
DDePS-2a NL FEA	10.0	HP180x10

Table 7. Difference in mass for the designs obtained with the methods discussed in this paper.

Method	Difference in mass w.r.t PC rules + linear
PC rules + linear	0%
PC rules + non-linear	-4%
Improved NL FEA PC	-5%
DDePS-2a NL FEA	-11%

obtained by also determining the shell plate thickness by direct calculations.

The DDePS-2a NL FEA method has even a higher reduction but is less conservative. It may therefore be less appropriate to use the DDePS-2a NL FEA method for the design of dedicated polar frigates as the safety margin in the design is reduced. However, for non-dedicated frigates that may only operate incidentally in ice floe infested waters this may be an interesting approach to achieve a certain level of ice worthiness with limited impact on the overall operational envelope. Furthermore, a more far-reaching method may also allow alternative (optimised) designs that are not allowed by following the PC rules. In this paper, only manual optimisation has been performed without changing frame and stiffener spacings, only plate thickness and stiffener scantlings. This is an practical engineering approach. An automated optimisation tool may enable even lighter weight structures.

In addition, the PC rules approaches are validated with experience since the approaches are used for design of ships that are sailing in ice floe infested waters. For the DDePS-2a NL FEA method this is not the case and it would be recommended to validate this approach by full-scale field trials in the future.

5.2 *Design load*

For the DDePS-2a NL FEA method two different load patches have been used. The load patch that is based on a representative medium first-year ice load shows to be more severe than the load patch representative for the PC rules based ice load. From Figures 9 and 10 it is observed that "patch 1" causes the largest deformations. Two primary factors have been identified that cause "patch 1" to be the most severe:

1. Magnitude of the ice load;
2. Dimensions of the contact area.

The effect of the contact area dimensions is postulated to have the strongest effect. The contact area of "patch 1" is relatively short and spans just over one transverse spacing (0.375 m) at the end of the contact. "Patch 2" almost spans four transverse spacings at the end of the contact. This means that only a small amount of transverses are carrying the load at any given time during the contact for "patch 1" compared to the other scenarios. This reduces the load-carrying capacity of the structure significantly.

For future work it would be of interest to reflect on the used inputs that are deemed representative for a certain ice load and how this compares to the resulting load. Using an overly stringent load results in unrealistic designs. This may result in non-ice strengthened ships to avoid operating incidentally in ice floe infested waters, while that could be safely done.

In addition, a moving ice load is recommended here as it represents a more realistic load. However, the DDePS-2a NL FEA method uses a simplified rectangular load patch to do so. If one aspires to have a more realistic load for design purposes it may be more appropriate to maintain the triangular or trapezoidal contact area. For future work it is recommended to investigate the implications of using a simplified rectangular load patch on the structural response compared to a more realistic triangular or trapezoidal one.

5.3 *Multi-impact*

The multi-impact analyses show that multi-impact scenarios may matter for designs where plastic deformation is allowed. The implications of this may be limited for design loads which are based on very extreme loads such as 1-in-100 year loads. However, if a design is based on a design load that may occur more frequently or if a more frequent load with a lower magnitude still causes plastic deformation than multi-impact may become relevant. For these cases it is recommended to perform multi-impact analyses and investigate whether the amount of impacts required to reach an unacceptable threshold is likely to be exceeded during operation.

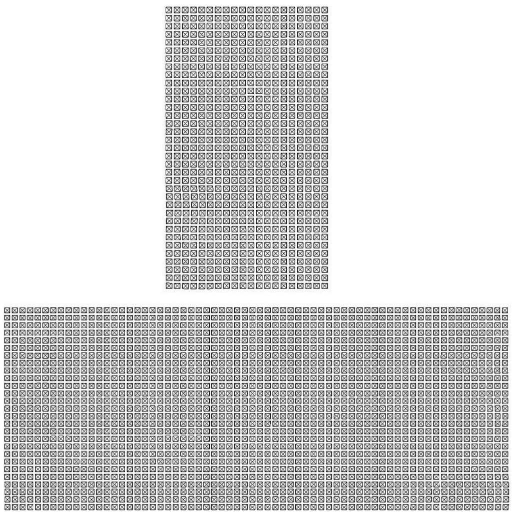

Figure 16. Comparison of the final contact area of load "patch 1" (top) and "patch 2" (bottom) for the stationary impact load.

6 CONCLUSIONS

6.1 *Which weight reduction for a polar class design can be obtained using direct calculation methods?*

By comparing the mass of a section of the intermediate bow region of a PC6 frigate, an ice belt mass reduction of 11% has been obtained for the DDePS-2a NL FEA methodology with respect to a PC rules design with linear direct calculations. For the improved PC NL FEA approach a reduction of 5% has been obtained.

6.2 *To what extent do the two considered direct calculation methods yield different results?*

The DDePS-2a NL FEA direct calculation methodology results in a larger reduction of added structural mass. However, this method does remove a larger part of the safety margin compared to the improved PC NL FEA approach. This difference is mainly because the DDePS-2a NL FEA methodology allows the change of all scantlings whereas for the improved PC NL FEA approach this has been limited to the scantlings allowed by the PC rules.

6.3 *What is the effect of multi-impact on the PC6 designs in case small plastic deformations are allowed?*

A multi-impact scenario for a design where small plastic deformations are allowed results in an increasing permanent deformation of the structure. The permanent deformation converges to an equilibrium after a certain amount of impacts.

For extreme loads the implications are limited since it is not realistic that such a load occurs frequently. However, for realistic loads this effect may be important since a more frequent occurrence is more likely.

7 RECOMMENDATIONS

For the design of dedicated polar frigates it is more appropriate to use the improved PC NL FEA approach as it stays closer to the tried PC rules and maintains a larger safety margin. However, for the design of frigates operating incidentally in ice floe infested waters the use of a more far reaching approach such as the DDePS-2a NL FEA methodology should be explored.

For the DDePS-2a NL FEA methodology several recommendations are made.

First, it is recommended to investigate the effect of assuming a simplified rectangular load patch on the structural response compared to a more realistic triangular or trapezoidal contact shape.

Second, the use of medium first-year ice inputs results in a load patch that causes severer damage to the PC rules design than the PC rules design load patch. Further investigation of realistic ice load inputs for the DDePS-2a model and which inputs are suitable for incidental ice load design is therefore recommended.

Third, it is further recommended to compare the DDePS-2a NL FEA approach with more detailed and complex coupled approaches such as described in (Kim et al. 2015, Yu & Amdahl 2021).

Lastly, it is recommended to validate the approach with experimental results. Since this method is recommended for frigates operating incidentally in ice floe infested waters it is of importance to consider a more flexible hull instead of a rigid one (such as for icebreakers).

With respect to multi-impact, it is recommended to look into developing guidelines/methodology on dealing with multi-impact scenarios for the design and operation of non-ice strengthened frigates operating only incidentally in ice floe infested waters.

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