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Impacts of nonlinear vs. linear finite element analysis on ice-strengthened primary structures

Ville M. Valtonen[1]
[1] Aker Arctic Technology Inc, Helsinki, Finland

ABSTRACT

The IACS Polar Class (PC) rules divide the analysis of hull structures into two parts: shell plate and frames (secondary structure) are designed with rule equations which are based on plastic capacity of the structure. The primary structures (stringers and web frames) that support the shell and framing are designed using direct analysis which in practice means in most cases finite element analysis.

For the finite element analysis of primaries there are two options given in the PC rules. The typical and widely used option is linear analysis, where the primary structure is designed essentially to an elastic limit. Linear analysis is relatively straightforward and well-established practice and clear acceptance criteria exist. However, as different acceptance criteria than for shell plate and framing is used, it results in an imbalance between primary and secondary structure. Experience has shown that this imbalance usually results in excessively heavy primaries for high ice class vessels.

The second option, nonlinear analysis, is a more involved procedure and guidelines and acceptance criteria for the analysis are still under development. When all structures are designed with the same type of acceptance criteria the result is a more balanced and typically more lightweight structure. Moreover, plastic analysis gives significantly more insight into the capacity and behavior of the structure at overload, enhancing safety. Despite these advantages nonlinear analysis has not been used in the design of built vessels thus far.

In this paper, an example vessel is analyzed with both methods and for both low and high ice classes to demonstrate the impact of nonlinear analysis on the design of the primary structure. The results demonstrate the potential for weight saving on high ice classes, provide insight into when nonlinear analysis is beneficial, and ultimately, provide motivation and basis for the development of guidelines for nonlinear analysis as well as adoption of it as a tool for practical ship design.

KEY WORDS: Polar Class, FEM, Nonlinear, Primary structure

INTRODUCTION

The International Association of Classification Societies (IACS) produced harmonized rules for design of ice-going vessels in Polar waters, the Polar Class (PC) Rules, in 2006 (IACS, 2016). Currently, these rules have been widely adopted as the design basis for ice-going vessels operating in Polar waters, and practically all of these vessels are designed to either PC class rules or Russian Maritime Register of Shipping (RMRS) Rules (RMRS, 2018).

The design basis in PC rules is a glancing impact scenario where the bow of the vessel collides with the ice edge. The design ice load is derived from this scenario using the ship's parameters and the selected ice class. The ice load is modeled as a rectangular patch with evenly distributed pressure. The load patches of the same size are applied on all structural elements, the only difference being the peak pressure factor which accounts for the possibility of higher local loads on smaller areas. (Daley, 2000 & IACS, 2016)

The structure is allowed to yield under the design load but must have substantial reserve against collapse and rupture (Daley, 2001). The design limit state for the secondary structure (shell plating and framing) is the onset of a plastic hinge mechanism. This design limit state represents a point where the stress state is largely plastic, but the plastic strain and the deformation are small (Daley et al., 2001). In essence, the design limit is the point where the structure yields, but permanent deformation is minimal. To calculate this plastic limit point, equations are given in the rules for plating and framing (IACS, 2016).

For the primary structures (stringers and web frames), the PC rules require the scantlings to be dimensioned with direct analysis, which in practice is typically a finite element analysis. There are two possible options for a finite element analysis, either linear or nonlinear calculation (IACS, 2016).

The linear analysis is a relatively straightforward procedure, for which the methodology has been well established. Therefore, it has been widely adopted in the industry and can be considered to be currently the standard practice. In linear analysis, the limit state for the primary structure is taken as the yield limit of the material, albeit 115% of yield stress is allowed in the primary member flange (IACS, 2016) to account for some plasticity and to allow for local stress concentrations. The shear limit at member webs is taken as yield limit (IACS, 2016).

The nonlinear calculation is a more complicated procedure, which requires more thought into proper modeling practices, incrementation, stability, material model, buckling, etc. Moreover, the acceptance criteria given in current rules is more a goal-based requirement than simple pass/fail criteria, and the determination of exact criteria is largely up to individual Classification Society. For these reasons, nonlinear analysis has not been applied as a practical design tool to date.

The issue with using linear analysis as a design tool for primary structures arises from the use of the same design load to evaluate two different limit states: the plastic limit state for secondary structures and the elastic limit state for primary structures. In principle, applying more stringent criteria for primary structure could be considered sensible, as that would ensure some degree of structural hierarchy by ensuring that the primary structures are stronger than the secondary structures. The problem, however, is that since linear analysis gives only knowledge of the structural response in the elastic region, there is no knowledge of the structural response beyond yielding. Thus, the amount of the plastic reserve is unknown, as illustrated in Figure 1.

Experience has shown that typically linear analysis leads to primaries that are relatively heavier compared to the secondary structure than on several proven vessels designed to earlier rules.

These vessels have long service history on harsh Arctic conditions without damages related to framing or primary members, which indicates that the primary structure on these vessels has been sufficiently strong.

This imbalance of relatively heavier primaries may lie in the difference of limit states used for the structural elements. By using nonlinear analysis, all structural elements are compared against similar criteria, and the resulting structure should be more balanced. Moreover, as the behavior of the structure is better known, the safety can be improved as there is explicit knowledge of the size of the available margin between design load and structural failure, whereas in linear analysis the amount of plastic reserve is not known.

A study of a typical polar vessel was done to investigate the effects and potential benefits of using nonlinear analysis to dimension primary structures. The aim is to quantify the effect of linear/nonlinear analysis on scantlings and to investigate if nonlinear analysis would improve the alignment the primary structure scantlings with the secondary structures. The results of the study are presented in this paper.

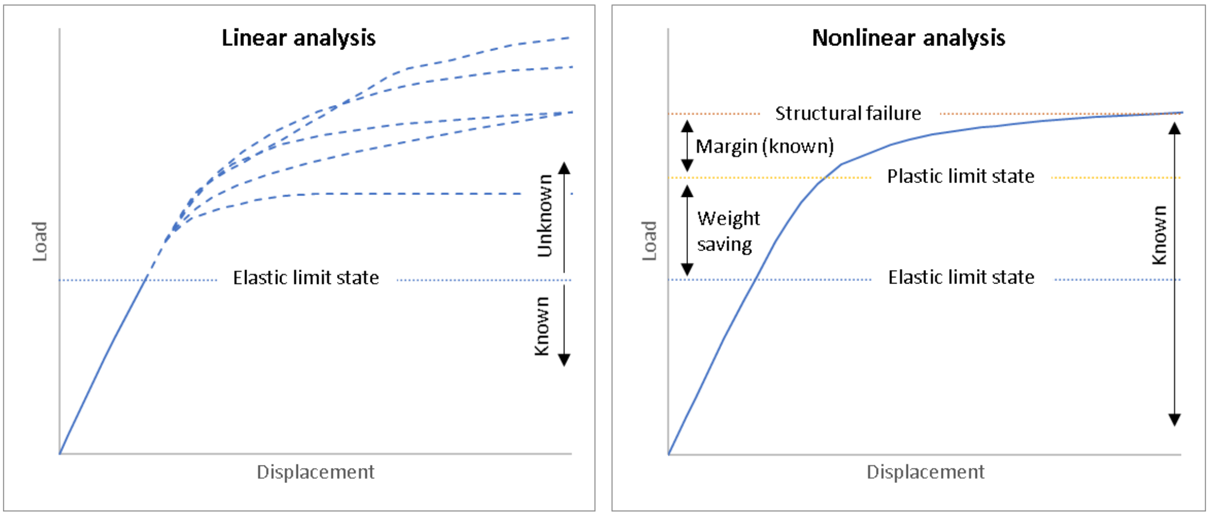

Figure 1. Load-displacement curves and limit states in linear and nonlinear analysis

Example ship

To investigate and demonstrate the effects of linear and nonlinear analyses on the design of the primary structures, an example vessel was used as benchmark. The vessel was chosen to represent a typical polar icebreaker/research vessel/small cargo vessel. The main dimensions were chosen as shown in Table 1.. The vessel was analyzed using both linear and nonlinear techniques and under three different loading conditions corresponding to ice classes PC6, PC4, and PC2. The minimum dimensions of the primaries were determined for each case according to rule requirements and the influence on the scantlings of the different analysis techniques was investigated.

Table 1. Main dimensions of the example vessel

Δ	25000 t	Displacement
L_{oa}	abt. 175 m	Length overall
B	24 m	Beam
T	8.5 m	Draft, max. icegoing
H	13.5 m	Side height

The structural configuration of the example vessel represents a typical arrangement for a polar vessel. The shell plating is supported by transverse framing with spacing of 800 mm and intermediate frames at 400 mm. Horizontal stringers are spaced at 1500 mm and the web frames spacing is 2400 mm. A double side is provided as per MARPOL, and web frames are arranged as plates through the double side. Depending on the ice class, the stringers are arranged as either open T-beams or as platforms, following well established design practices.

The double side width of 1600 mm is relatively narrow to highlight the differences between analysis methods as much as possible. In practice, the double side width depends on many considerations, such as damage stability, tank volumes, weight optimization and producibility. For typical high ice class vessels, a double side of approximately 1500 mm can be considered as the practical minimum. The structural arrangement for PC4 vessel is shown in Figure 2. The structural arrangements for PC6 and PC2 have similar principles and only the scantlings of the side shell and primaries have been changed. These arrangements are provided in Appendix A.

To ensure reasonable results that would be applicable to real-world vessels, some minimum scantlings were used. The minimum web height of the stringer was taken to be twice the height of the local frame. A minimum plate thickness of 9.0 mm was applied to all structures adjacent to side shell, as thinner structures would have high risk of buckling and would also be unlikely to fulfill the requirements of open water rules.

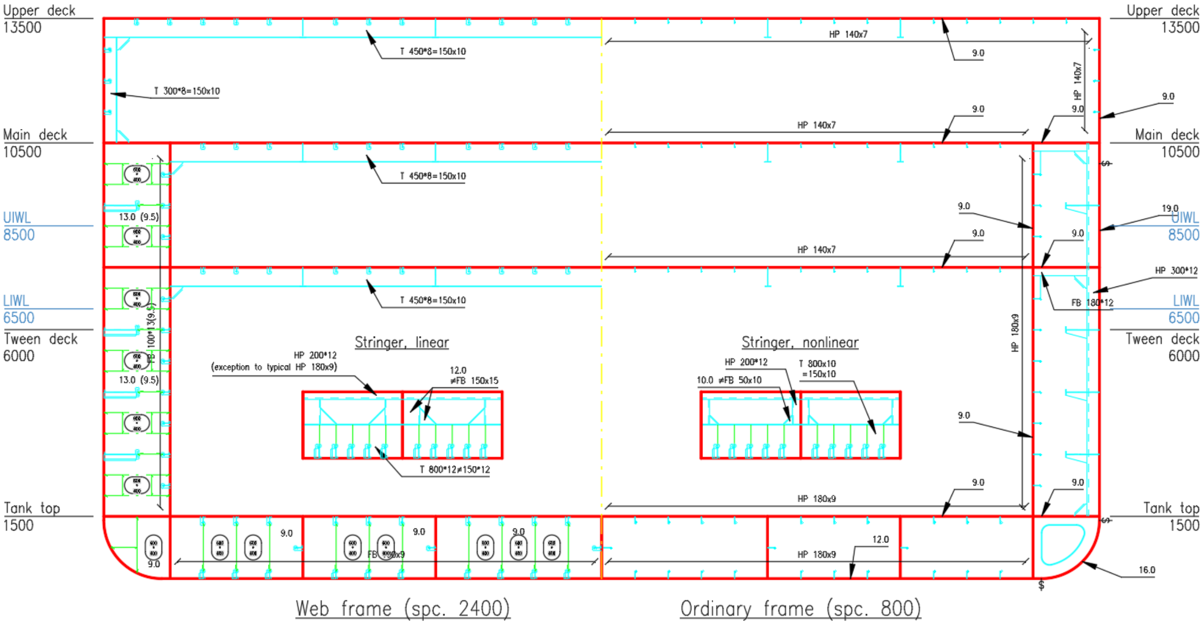

Figure 2. Structural arrangement of the example vessel, PC-4. Plain values refer to linear calculation and values in brackets to nonlinear calculation results

The analysis was done on the midbody icebelt region of the vessel. One benefit of analyzing the midbody is that the ice load depends primarily on the displacement of the vessel and not on the hull shape, which is largely influenced by the operational profile of the vessel. Furthermore, the prismatic midbody is easier to model than the complex curvatures of the bow and stern of ice-going vessels.

METHODS

Modeling

The analysis was done with Abaqus, version 2017. The structure was modeled as shell elements. All decks, bulkheads and primary structures were modeled as accurately as possible, including flanges, brackets, manholes and buckling stiffeners. The frames and longitudinals designed as bulb profiles were modeled as equivalent L-profiles according to IACS (2017). Small details such as cutouts, lugs and scallops were omitted from the model.

The longitudinal model extent is between two transverse bulkheads, as the bulkheads provide a natural support for the side shell structure. A typical bulkhead spacing of 5 web frame spacings (12.0 m) was selected. The vertical extent of the model is between the bottom and the upper deck and the transverse extent is limited by the centerline and the side shell. The model extents provide a sufficiently large model to ensure that boundaries do not affect the stress state of the primaries under consideration, while keeping the required computational effort reasonable.

The material for all structures is HT-36 grade shipbuilding steel with yield strength of 355 MPa, which is the most widely used steel for icebreaking ships. The material was modeled as bilinear elastic-plastic, with a plastic modulus E_T of 1000 MPa, similar to Pearson et al. (2015).

Mesh

The models were meshed with first order shell elements of type S4R. The mesh was created primarily from quadrilateral elements and triangular elements were used only where necessary to provide well shaped elements. The typical element size used was 100 mm x 100 mm, leading to a balance between accuracy and calculation effort. An example of the mesh used in the analyses is shown in Figure 3.

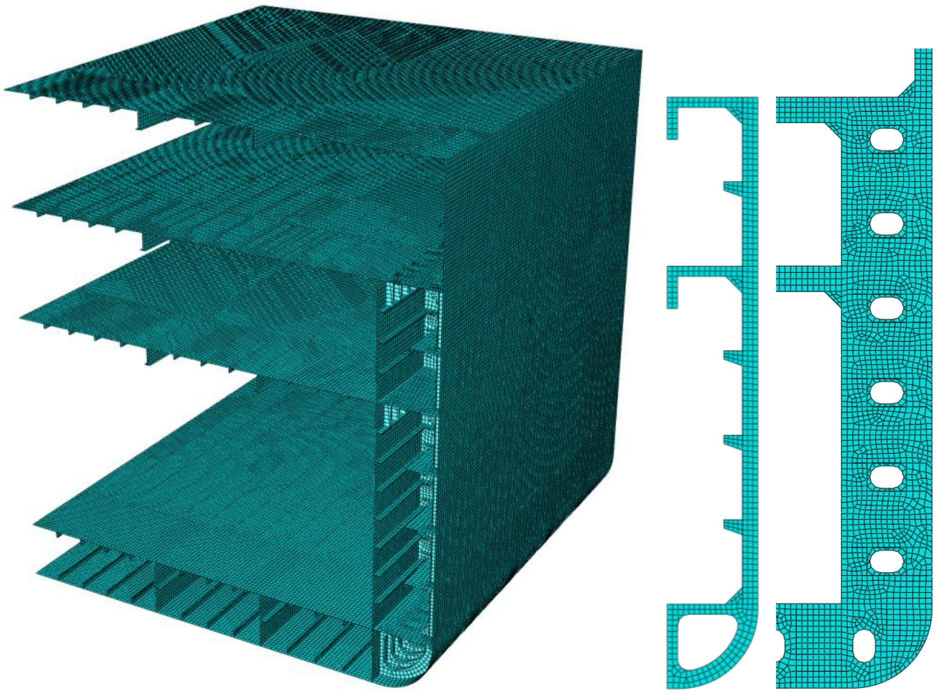

Figure 3. Mesh

Boundary conditions

Pinned boundary conditions were applied to the model at both ends (transverse bulkheads) and at centerline. The boundary conditions were applied at a sufficient distance from the load and the structures under consideration to minimize the effect on the calculation results. The boundary conditions are shown in Figure 4.

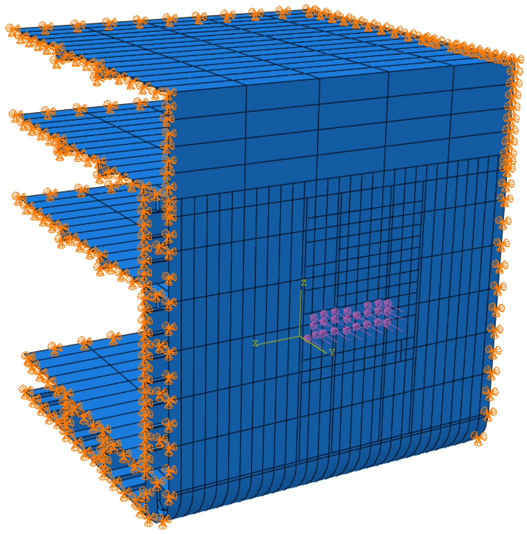

Figure 4. Boundary conditions and typical load applied to the model

Loads

The design loads were calculated according to IACS (2016) PC Rules for the midbody icebelt region. The load patch dimensions were adjusted to align with the mesh, while keeping the total force on the load patch constant. The loads were applied as evenly distributed pressure loads, perpendicular to the shell. The rule loads for each ice class and their respective implementation in the model are shown in Table 2.

Table 2. Ice load for each ice class, as calculated with rules (IACS, 2016) and as applied to model with dimensions slightly modified to align with the mesh

	Load patch, rules			Load patch, model		
Ice class	**w** (m)	**b** (m)	**p** (kPa)	**w** (m)	**b** (m)	**p** (kPa)
PC-6	2.821	0.784	1380	3.00	0.75	1356
PC-4	2.971	0.825	2852	3.00	0.75	3107
PC-2	3.277	0.910	6088	3.20	0.90	6305

The load patch was applied to several locations to determine the most onerous location for each structural element. The load patch locations are shown in Figure 5. A typical case of load application is shown in Figure 4.

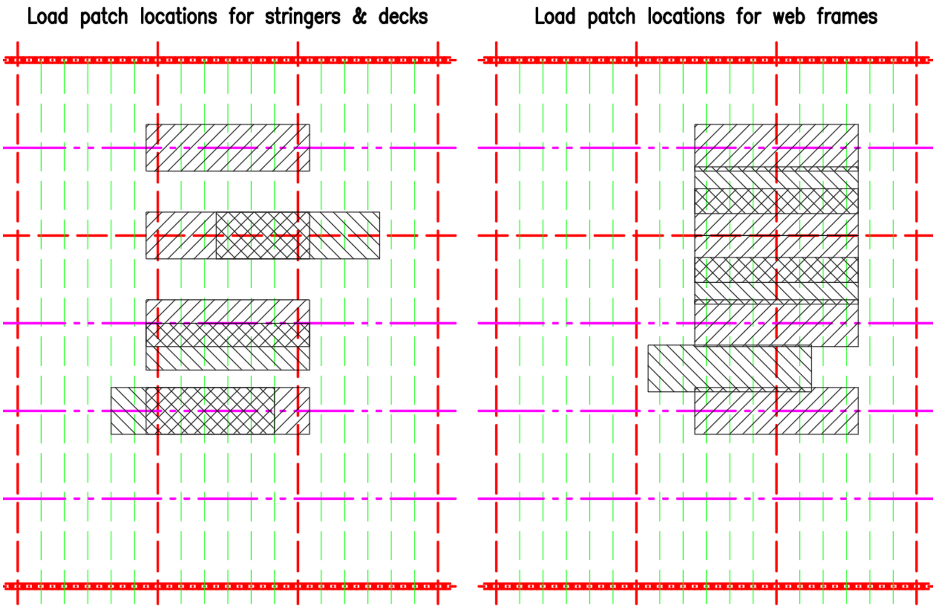

Figure 5. Locations where load patch was applied to find the most onerous one

Acceptance criteria

For the linear analysis, the acceptance criteria were used as described in the IACS (2016) PC Rules, requirement I2.17.5. These requirements limit the shear stress in primary member webs to be maximum $\tau_{allowed} = \sigma_{yield}/\sqrt{3} = 205.0$ MPa . In member flanges, the allowed maximum stress is $\sigma_{allowed} = 1.15\sigma_{yield} = 408.3$ MPa. These requirements were also applied to brackets that connect the stringers and web frames to other primary structures. The requirement to fulfil relevant buckling criteria was applied by requiring that the critical buckling load must be greater than the design ice load.

For the nonlinear analysis, no harmonized, widely accepted criteria exist. The only classification society rules where a plastic limit acceptance criterion has been defined based on the IACS PC rules are the RMRS (2018) rules. The RMRS criteria is based on the load-displacement curve and the ultimate plastic capacity P_{ult} of the primary structure is determined by the modified tangent intersection method as shown in Figure 6. P_{ult} must exceed the design load for the structure to be accepted.

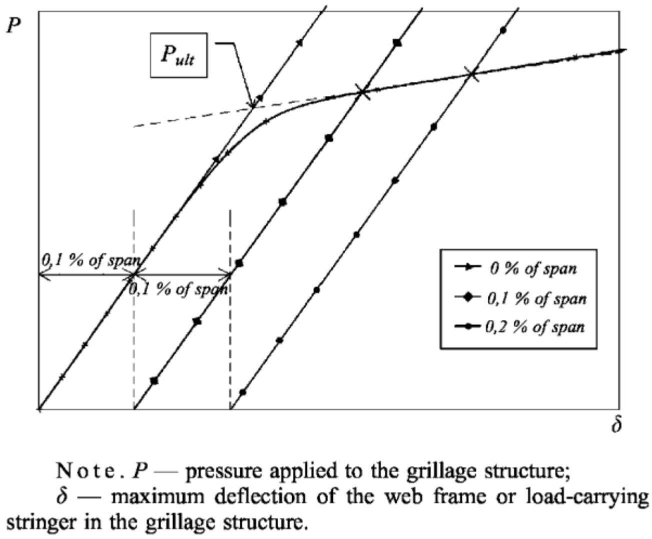

Figure 6. RMRS criteria for determining P_{ult} for the primary structure (RMRS, 2018)

Lloyd's Register (LR) has proposed an acceptance criterion based on equivalent plastic strain. The LR criteria requires that the plastic strain at 150 % of the design load is less than 2.5% and is based on analyzing earlier designs that have performed well. (Pearson et at., 2015)

In addition, several acceptance criteria proposals exist which are not made publicly available.

During this study, the LR criteria was found to be more stringent than the RMRS criteria and was chosen as basis for this study since the structures would pass both criteria and the resulting weight saving potentials would therefore be conservative.

Both linear and nonlinear analyses were run on a set of initially selected scantlings and iterated until a solution was found which passed the criteria while being as lightweight as possible. The number of iterations it took to achieve this varied between 3 and 15 for the different cases.

RESULTS

The final scantlings for each case are shown in Table 3.

Table 3. Final scantlings for primary members for each calculated ice class; All web frames

and stringers for PC-2 are stiffened plate structures through the double side

Ice class	Stringer		Web frame	
	Linear	Nonlinear	Linear	Nonlinear
PC-6	T-400x11=100x11	T-400x9=100x9	9.0	9.0
PC-4	T-800x12=150x12	T-800x10=150x10	13.0	9.5
PC-2	18.0	11.5	19.0	14.0

The weight of the structure was calculated for each case by summing the weights of individual parts. The calculated weight for primaries includes the primary members, stiffeners of the primary members and brackets as applicable. The results of the weight calculation are shown in Figure 7.

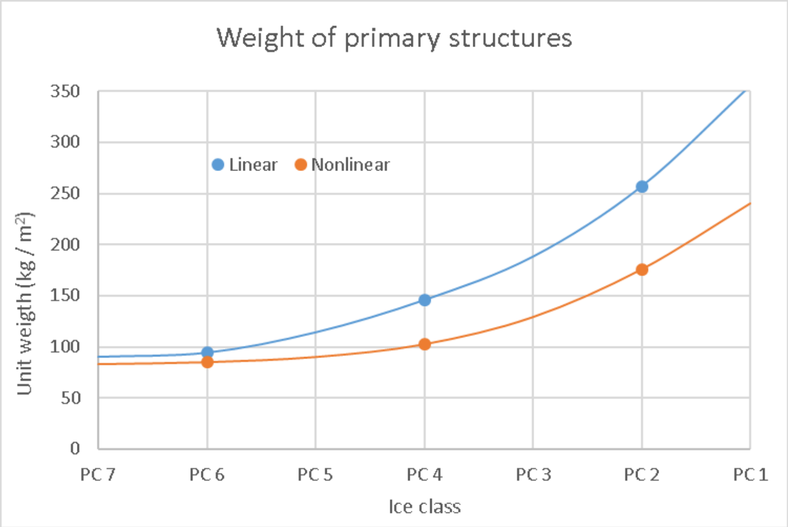

Figure 7. The calculated weight of primary structure with linear and nonlinear analysis

CONCLUSIONS

The results show that for a low PC class vessel (PC7 or PC6), the weight difference between structures dimensioned using linear analysis and nonlinear analysis is insignificant, and the additional effort of nonlinear analysis is not justified. For a vessel of medium PC class, such as PC4 and in some cases PC5, nonlinear analysis can reduce the steel weight, but the change is relatively small and nonlinear analysis is only worthwhile for vessels which are weight-critical, such as shallow draft vessels and naval vessels.

For a high ice class vessel, typically PC3 and above, the nonlinear calculation provides significant reduction in the scantlings of the primary structures, which significantly lowers the steel weight for a typical vessel. Moreover, the reduction in scantlings for the typically thick primary members improves production efficiency considerably. Thus, for a high ice class vessel, nonlinear analysis of primary structures would typically be worth the required extra effort, and as discussed in the introduction, would result in a more balanced design where the strength of primaries would match that of the shell plate and framing. The results of the nonlinear analysis align well with experience from past designs, whereas the results from linear analysis lead to primary structures which are significantly heavier than those of successful past designs.

Furthermore, the nonlinear analysis would improve the safety of the structure, as the analysis would provide better understanding of the behavior of the structure at the design load and over. It helps prevent designs where the load carrying capacity is lost due to buckling or other unexpected effects which the linear analysis does not give full insight into.

In order to transform nonlinear analysis from a research tool to a practical design tool, clear guidelines on modeling practices, analysis procedure and acceptance criteria are needed. The possibility of using nonlinear analysis for primary structures helps improve the safety of high ice class vessels while reducing weight and thus improving the efficiency and reducing the price of these vessels. These guidelines should be developed and implemented into IACS and Classification society rules as soon as possible.

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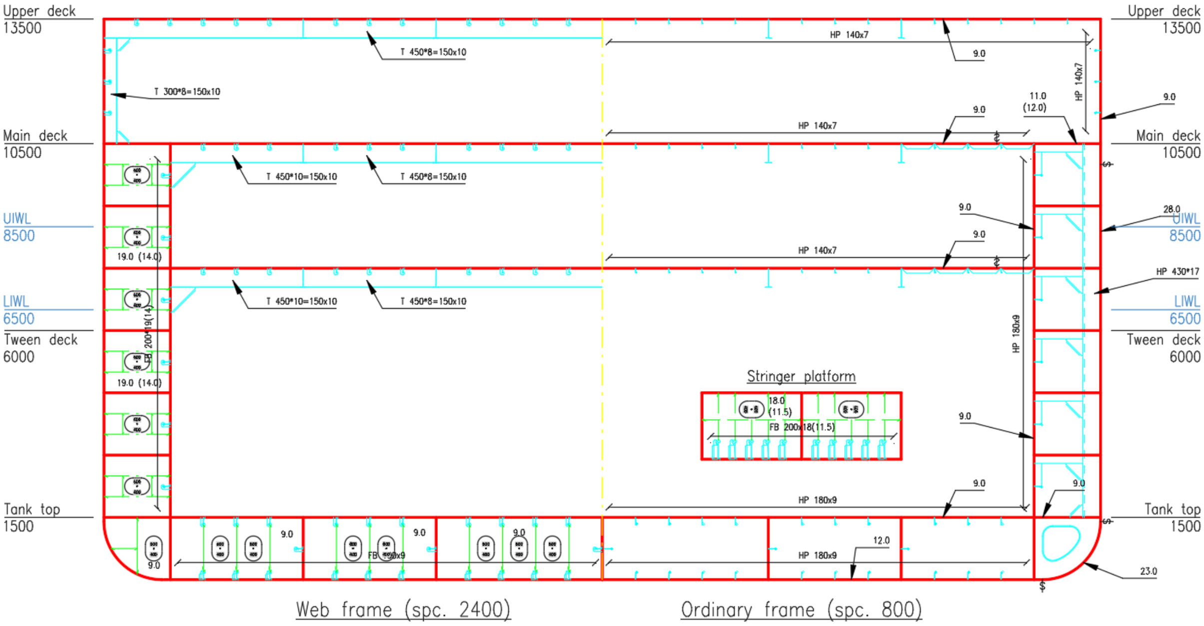
APPENDIX A STRUCTURAL ARRANGEMENTS FOR OTHER ICE CLASSES

PC-2

Plain values refer to results of linear analysis and values in brackets to results of nonlinear analysis.



PC-6

Plain values refer to results of linear analysis and values in brackets to results of nonlinear analysis.