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Ice Class conversion for a cruise vessel: comparative FE structural assessment for Ice Belt installation

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Abstract

As part of an extensive conversion project, the hull structures of a luxury cruise vessel have been reinforced to meet IC Ice Class notation. Because of the age of the vessel and the extent of modification needed to meet IC notation, an alternative solution, in the form of doubler plates achieving equivalent plate thickness, has been agreed with Class to satisfy applicable Ice Class structural requirements.

This study presents the FEM structural evaluation of this alternative arrangement, run in comparison to standard arrangements.
Specific focus has been given in the evaluation of local structural response to ice pressure load in way of Ice Belt.

Keywords: Ice Class, Ice belt, vessel conversion, cruise ship, cruise vessel, ship design, finite element analysis, structural analysis, MAESTRO

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1. Introduction

As part of an extensive conversion project, the existing cruise vessel subject of the present study has undergone structural reinforcements in order to gain IC ice class notation.

The combination of several factors, such as the age of the vessel, the time frame available for drydock, but also the vessel's existing structural topology, lead to the elaboration of a custom structural arrangement, in agreement with Class to satisfy the requirements of Ice Class Rules.

The main objective of the present study was the comparative assessment of the structural equivalence of doubler shell plates, presented as an alternative design to the standard structural requirements contained in Finnish Swedish Rules (85 Edition), which have been deemed as applicable reference for the vessel in object.

Specific interest has been applied for:

- Shell thickness equivalence
- Welding process and detail of applied connection
- Response evaluation to longitudinally varying ice pressure load
- Fine Mesh analysis for shell doubler installation

2. Ice Class Regulations

2.1. *General*

Whether for a new construction, or a conversion, the ice class notation requires a certain number of features to be cared for:

- Reinforced structure in way of the ship's waterplane. The so-called *Ice-Belt*
- Hull form itself
- Propulsion and shaft line(s)
- Reinforced propeller blades
- See chest(s): specific requirements
- Appendage design and protection
- Towline arrangement
- etc.

Depending on the intended service, and zones and seasonal period of navigation, several Ice Classes are offered by the Administration [1]. The conversion of the present vessel is aiming for a notation IC, which is assigned to vessels shipping all year round in waters having a maximum ice concentration of 1/10.

The current study deals with the structural ice-belt. The other topics are out of the scope of this study.

2.2. *Structural Ice-belt*

Ice Class Regulations identify 3 regions along the length of the vessel for ice strengthening, and the vertical extent will depend on the Ice Class. It extends namely from 0.5m below lower waterline, to 0.4m above maximum waterline for class IC.

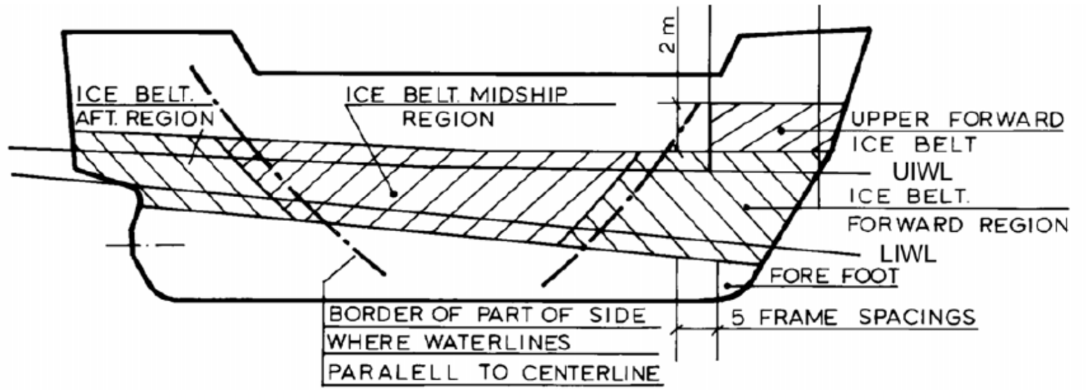


Fig. 1 Ice Belt Regions definition

Structural analysis for Ice Class notation includes the verification of several structural elements, summarized below:

- Shell, deck and transversal bulkhead plating
- Ordinary stiffeners in way of Ice Belt, with eventual introduction of intermediate frames
- Reinforced stiffeners and girders

Specifically, the strengthened shell plating thickness is governed by the structural frame spacing, and the ice pressure (but also total displacement and installed propulsion power), according to formulation below:

$$t = 667 \cdot s \cdot \sqrt{\frac{f_1 \cdot p_{PL}}{\sigma_y}} + t_c \ \ [mm] \qquad (1)$$

Where f_1 is a coefficient, p_{PL} is refence ice pressure for plating, s is local frame spacing, σ_y is material yield stress and t_c is a thickness increases for ice abrasion effects.

Because of the highly different flexural strength between a frame and the mid-span between frames, the ice pressure follows a certain load distribution, as shown in figure 2 below:

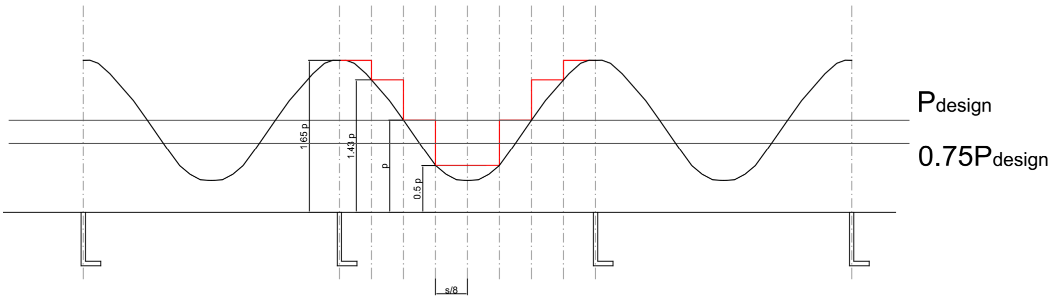


Fig. 2 Longitudinal pressure distribution due to ice compression

Such relation provides the minimum (Rule) thickness that shell plating must meet in way of Ice Belt for obtaining corresponding ice class notation.

For the present application, the respect of thickness in (1) would have meant extensive reconstruction of the vessel’s hull structure in way of the ice belt.

Practically this would have involved the complete dismantling/ removal of a vertical hull “stripe” of 1.5 metres height all around the ship, replaced by a prefabricated one of increased thickness.

According to Class Technical Committee advice, doubler installation on existing hull plating has been acknowledged as a satisfactory equivalent measure in terms of rule thickness requirements.

With this alternative approach, determination of total thicknesses based on following formula:

$$t_{eq} = \sqrt{(t_{shell})^2 + (t_{doubler})^2} \ \ [mm] \qquad (2)$$

Where t_{eq} is the total thickness for the doubler installation, while t_{shell} and $t_{doubler}$ are respectively original shell and applied doubler thicknesses.

Definition of doublers has, thus, been completed basing on local shell thickness, hull shapes and local interferences (shell doors, scuppers, overboard penetrations, etc…) and recalling that doublers are deemed acceptable when having a maximum vertical extent of 30 times relevant thickness.

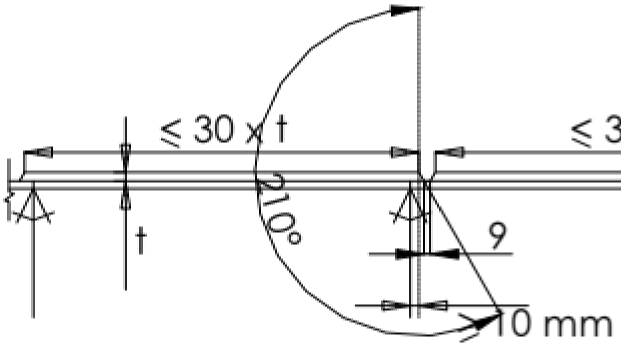


Fig. 3 Structural description of doubler installation.

3. Software tools

The finite-element structural models were developed in MAESTRO Marine. The software is very "marine" in its philosophy: FE models can be analysed in "dry" mode as well as wetted mode, meaning that the model is hydrostatically balanced, taking into account tank fillings, deck loads, still water and wave profiles, etc.

The other feature of MAESTRO Marine, directly interesting to the present study, is the capability to embed a local fine mesh model into the global coarse model, the local model receiving automatically boundary conditions from the global one.

Cross-sectional detail analysis has been developed with Z88 Aurora, a mechanical oriented powerful complete FEM application developed by Bayreuth University, capable of solving non-linear, thermal and thermomechanical analysis.

4. The Vessel

4.1. Main Particulars

The vessel subject of the current study is a luxury cruise vessel originally launched in 1992.

Her main are summarized in **Table 1** below.

Table 1 Reference Cruise Ship Main Particulars

Length Overall	155.80 m
Length Between Perpendiculars	134.2 m
Breadth Moulded	21.4 m
Depth Moulded	7.6 m
Draft	5.7 m
Passengers (Polar Condition)	240

In 2017 the vessel underwent an extensive conversion for the new service as Polar Expedition Cruise vessel. The conversion included structural modification for IC notation, a new ice class bulb, a new Observation Lounge, several machinery improvements and a complete refurbishment of accommodations.

Following figures (**Fig. 4** & **Fig. 5**) provide a quick glance of the vessel prior and after the drydock.

Fig. 4 Reference vessel prior to conversion.

Fig. 5 Reference vessel in new Polar service.

4.2. Ice-Belt extent/ doublers

The ice-belt is longitudinally distinguished into 3 regions (forward, midship and aft), with different ice pressures. The scantling requirements are also variable with height above and below the waterline, leading to a total of 60 distinct doubler plates to constitute the complete ice belt reinforced shell plating.

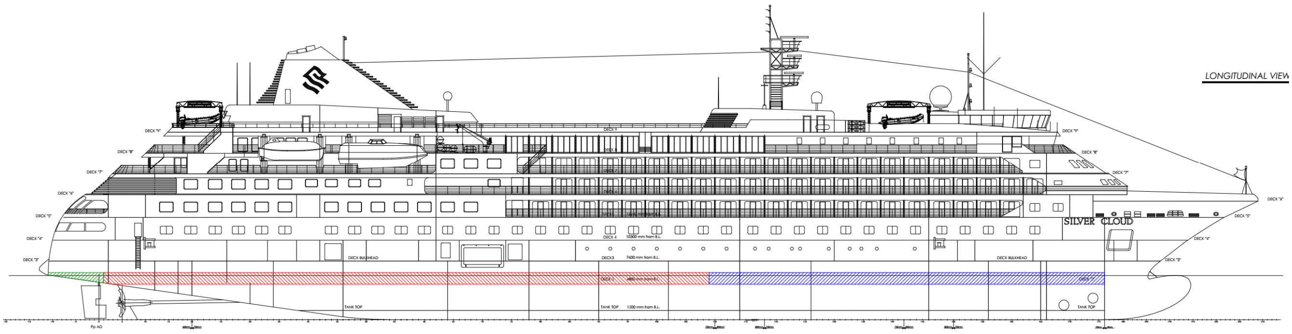


Fig. 6 Ice Regions definition

All 60 doublers have been systematically analysed in terms of nodal displacements and Von Mises stresses, in a comparative fashion: doubler plate vs standard thickness plates.

This comparative study required to produce 2 FE models: one featuring standard plating thicknesses as per strict Rule application, and one featuring equivalent doubler-plating.

A useful feature of MAESTRO Marine is its capacity to handle multiple load cases within one same model, meaning that all together only 2 FE models needed be prepared, to manage a total of 2 x 60 = 120 load cases.

5. 3-step global coarse mesh analysis

To assess the influence of the extent of the FE model onto the results, 3 models were developed and comparatively analysed:

Step 1: "Hybrid model"

Full length model but limited in breadth (from 6300 mm from CL to Side) and height (from tank top to Deck 3). Model size is about 11,000 elements

This setup gathers a large time saving in terms of Modeling due to the significant simplification but requires extensive use of external restraints to achieve model balance, leading to results affected by the boundary conditions.

Step 2: Full model with restraints

Whole hull geometry modelled, with application of external restraints for model balance. Model size is about 25,000 elements

The extended model provides better geometrical description of the vessel's structures, yet the results are still affected by the application of external restraints.

Step 3: Full model with transversal symmetry

Complete hull model with transversal symmetry, with only 2 restraints at extreme fore and aft ends to prevent model translation and rotation, leading to a more physically adherent structural description. Model size is about 25,000 elements, and 60,000 elements with doublers fitted.

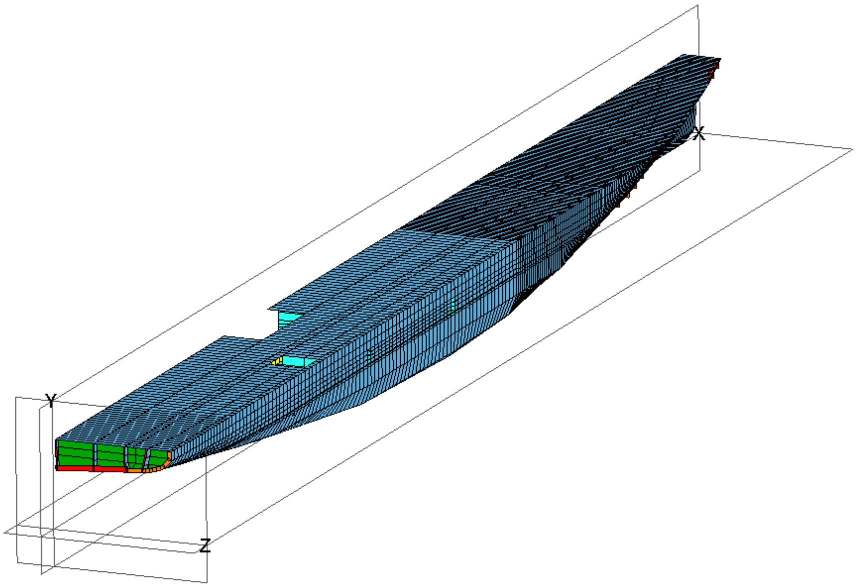


Fig. 7 Full ship model in MAESTRO Marine

It was observed that the global output is significantly influenced by model geometrical description and extent. For a given load case, refining the structural description lead to observed stress decrease of up to 48% from Step 1 to Step 3 models

Step 3-model was used throughout the rest of the study

6. Global coarse mesh analysis: Findings

Models with and without doublers were run with all the 60 described load cases, acting singularly and assuming whole doubler area as subject to design constant pressure. Max Von Mises stresses and nodal displacements were compared between the 2 models.

A very good alignment was observed between models, both in terms of nodal displacements and equivalent stresses (see figure below). Moreover, disregarding extreme load cases (affected by boundary conditions, globally all doublers show a good reference trend for stress outputs.

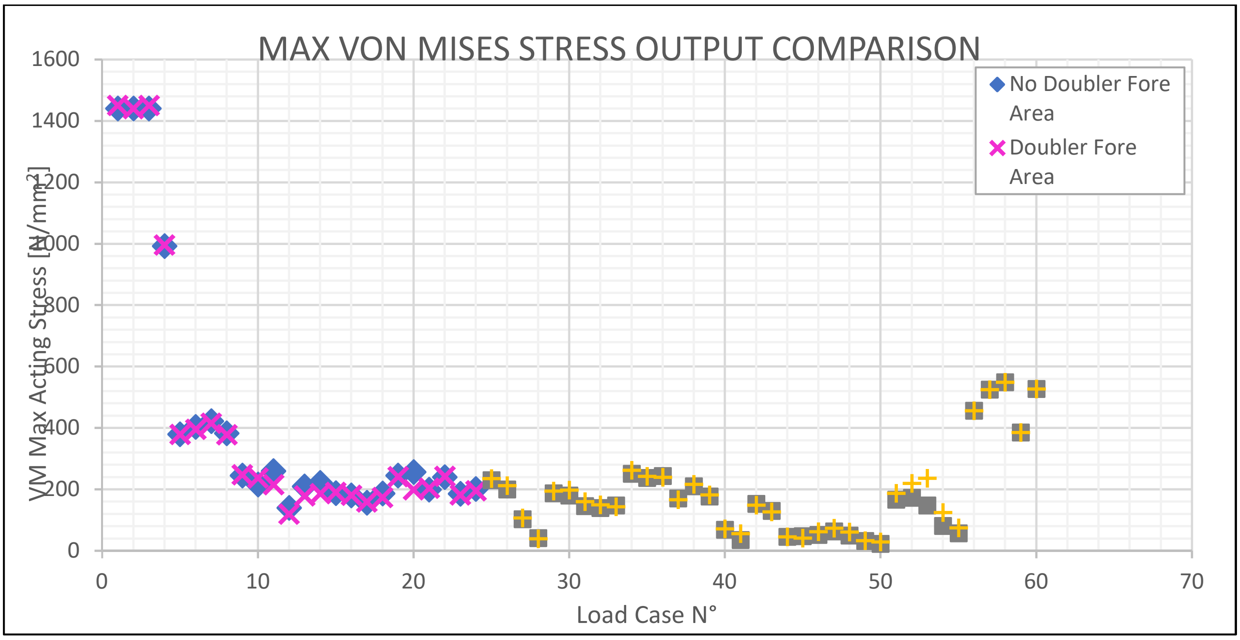
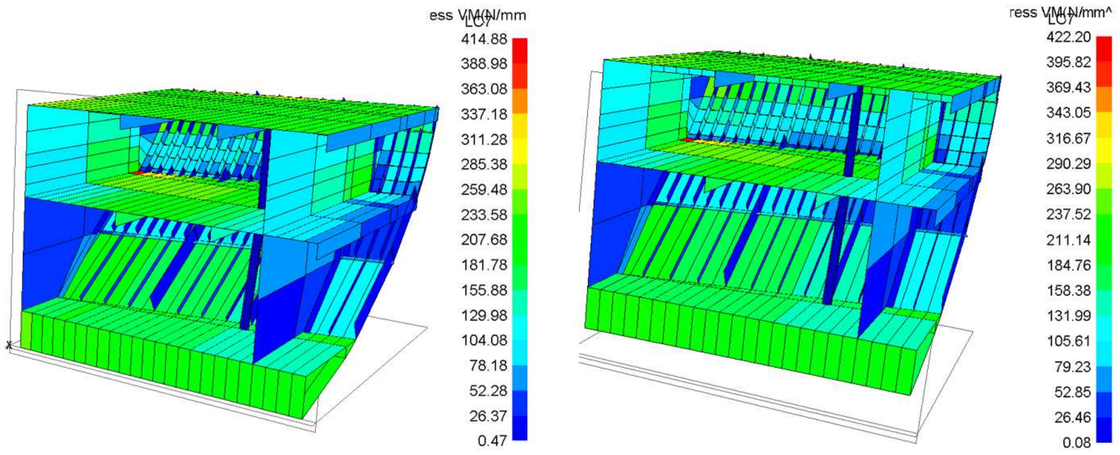


Fig. 8 Max Von Mises stress output comparison – 60 doublers



MODEL WITH DOUBLER PLATING (DCloud1C1.mdl)
Max Von Mises Stress = 414.9 N/mm2

MODEL WITH NO DOUBLER PLATING (Cloud1C1.mdl)
Max Von Mises Stress = 422.2 N/mm2

Fig. 9 VM stress map comparison – Load case 7 (Doubler 7, frames 134 -146, 3° row from top, Deck 2 level)

7. Embedded Fine Mesh Analysis

The coarse mesh model and the fine mesh model are tightly connected by rigid “Rspline” elements.

One RSpline will rigidly connect one edge of the coarse mesh (2 nodes) to a group of nodes of the fine mesh, located between the two defined reference nodes of the coarse mesh, and transferring displacement from coarse mesh nodes to fine mesh nodes.

In an embedded fine mesh/ coarse mesh analysis, both meshes are solved together, as they are closely coupled.

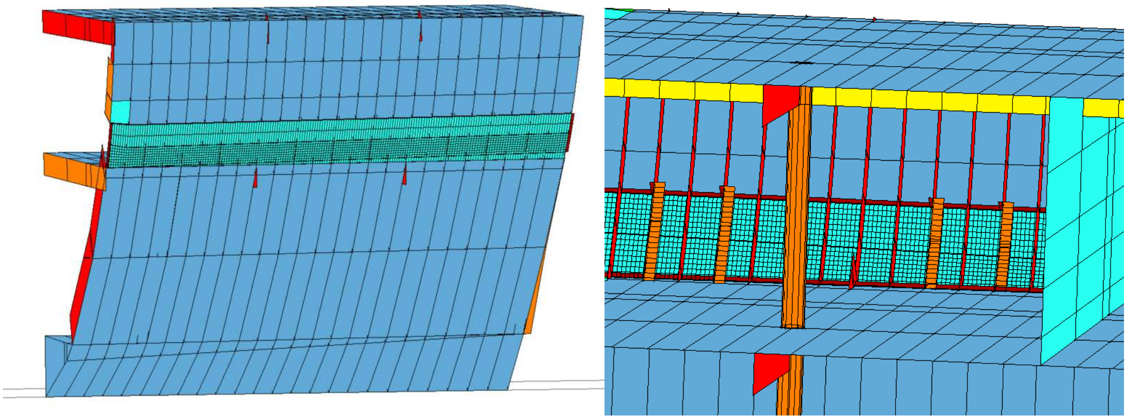


Fig. 10 Fine mesh embedded in global coarse mesh (outside view, internal view)

This further analysis has been performed for the detail evaluation of varying ice pressure loads, as introduced in 2.2.

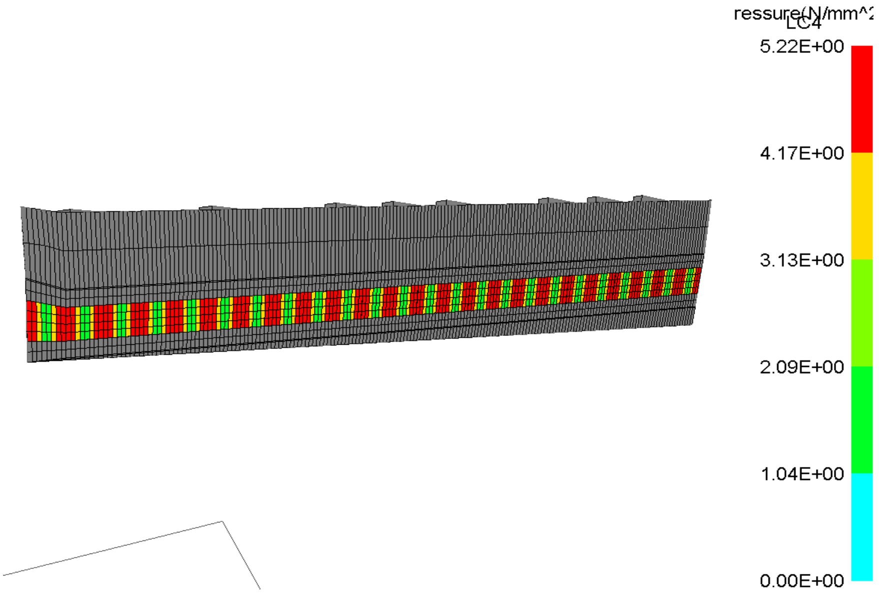
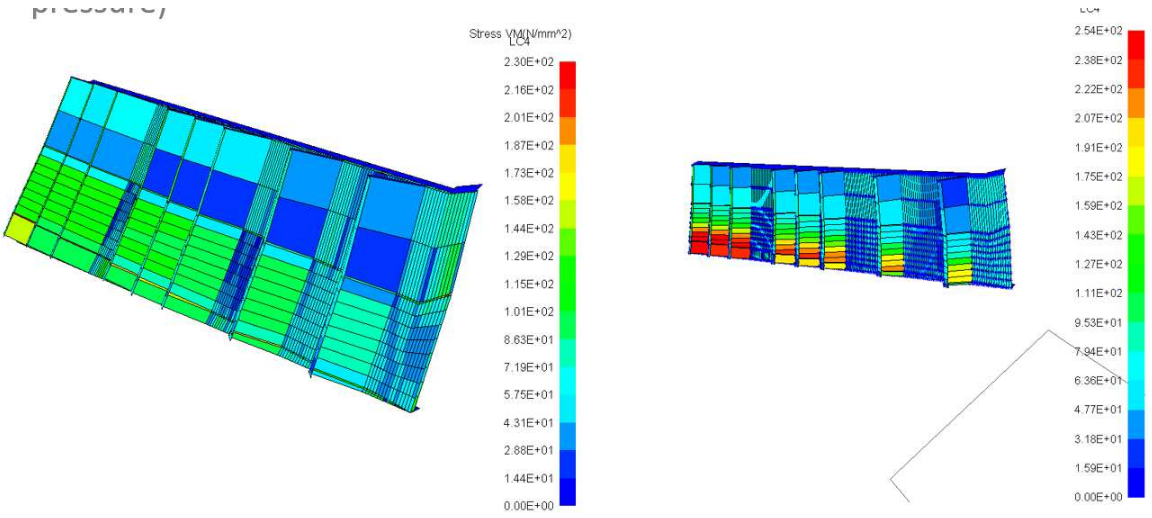


Fig. 11 Detail of varying ice pressure load on fine mesh element modelling trend of **Fig. 2**

Outputs suggest that, under applied hypotheses, doublers installation tends to displace higher values of stress towards edge connections and shows a slight decrease of stress level in the original shell plating.

Global behaviour is, in any case, aligned in both configurations.



MODEL WITH DOUBLER PLATING (Dcloud_1Gc.mdl)
Max Von Mises Stress = 230 N/mm2

MODEL WITH NO DOUBLER PLATING (Cloud_1G3d.mdl)
Max Von Mises Stress = 254 N/mm2

Fig. 12 Von Mises stresses, fine mesh model

8. Weld cross-section detailed analysis

As a further step, an additional investigation on the local behaviour of plating has been performed via a dedicate plain stress analysis. Scope of this local verification was to evaluate behaviour of welding throat and effectiveness of welding connections for doubler installation, evaluating stress concentration factors in doubler edges. Such study has been performed with Z88 Aurora software.

Key points of this evaluation can be summarized below:

- Comparative local analysis based on ice load pressure acting in different positions along a doubler (central, upper edge, lower edge)
- 2-D study based on a unitary thickness of shell subject to worst ice pressure (vessel’s fore region)
- Comparative analysis including equivalent thickness, doubler installation and full penetration welding

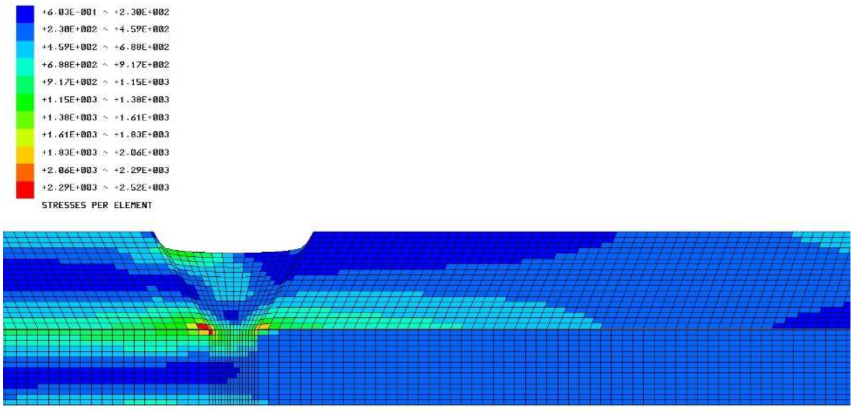


Fig. 13 Stress response in way of doubler cross-section

Such additional evaluation underlines that, subject to worst reference load case, realistic doubler connection (on the right in below image) presents a stress concentration factor of about 3, which correlates with usual behaviour of full penetration welding connection.

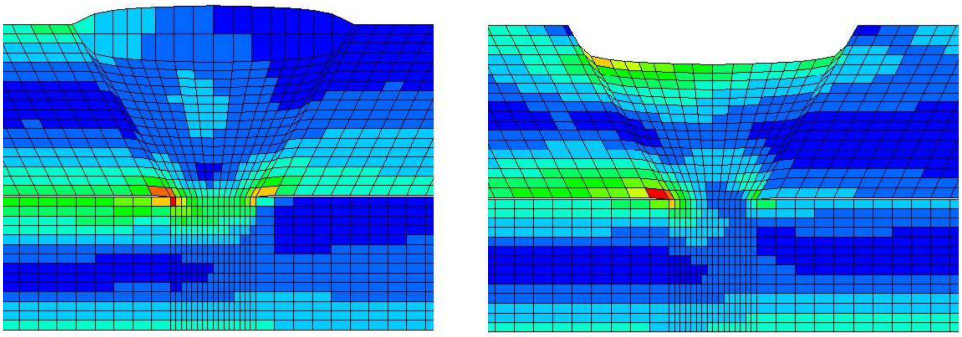


Fig. 14 – Direct comparison of local VM stresses in 2D Plain Stress model: effect of welding profile.

9. Next Steps

This study is now complete, and is undergoing final formal approval by RINA to achieve IC Class Notation. Yet the possibilities offered by the software employed opens further fields of investigation, both in terms of engineering, and ship operation and life-cycle management:

- Replicate ice pressure analysis with realistic load case and corresponding hydrostatic equilibrium: weight distribution, tank filling, wave profile

- Limit-state analysis: In addition to calculating displacements and stresses, MAESTRO can also perform a failure evaluation of the principal structural members, so-called Limit State analysis [2]. The Limit State analysis is the automatic verification of the load-bearing capability of a structural assembly, through the evaluation of 14 different failure modes (collapse in combined buckling, membrane failure, etc.). A second type of failure mode evaluation, based on the ALPS/ULSAP approach proposed by J.K Paik et al, of Pusan National University, Korea [3] is also proposed by MAESTRO, but adding a further set of limit state criteria to MAESTRO's cross-stiffened panel, combined load components, weld induced annealing, initial imperfections, local denting, etc. Limit state analysis is a valid tool at design stage, but will also accompany the vessel's life-cycle, by assessing the load bearing capability of hull structure taking into account observations from inspections: residuary plating deformations, dents, account of corrosion, etc).

- Only one step further to supporting at-sea operations, too: MAESTRO integrates a Seakeeping (3D-panel) code. The combined Hydrodynamic + structural code opens new areas of engineering analysis and behavioural prediction: ship motions, overall girder stiffness, assessment of passenger comfort taking into account waves, sea-states, ship speed and duration thereof when sailing in a seaway, extended consequences based on seakeeping analysis: extreme load analysis, fatigue analysis, all ensuing in voyage prediction, planning and critical decision making during the passage.

10. Conclusions

Direct comparison among coarse models with and without doublers displays a good alignment: no significant differences are highlighted either in terms of maximum nodal displacements, deformed models and Von Mises Stresses.

Structural FE model is significantly influenced by applied geometrical hypotheses and boundary conditions. This behaviour is observed in both models. with and without doubler installation.

Effect of fine meshing for significant doublers lead to an observed general decrease of stress levels. Such trend is confirmed in both models

Acknowledgements

We would like to acknowledge RINA Class Technical Committee for the close contact and cooperation shown during the development of the study.

References

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