Finite element modelling and strength analysis of hold No. 1 of bulk carriers

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Abstract

Bulk carriers are subject to SOLAS regulations concerning the structural integrity of hold No. 1. SOLAS Chapter XII Regulation 6 mandates that the transverse watertight bulkhead between the two foremost holds and double bottom of the foremost hold shall have sufficient strength to withstand flooding of the first hold. This regulation applies to all single-skin bulk carriers of 150 m in length and upwards constructed before 1 July 1999. IACS provides rules for the construction of these areas of such vessels in order to comply with SOLAS Chapter XII. This paper presents a methodology for modelling hold No. 1 of bulk carriers using finite elements in order to assess the structural integrity of these areas under the loads prescribed by IACS. Results from respective nonlinear analyses using IACS loads are also presented.

1. Introduction

In the following, the finite element model that has been developed at NTUA, within the framework of an FSA study on bulk carrier safety is described. A major part of this paper is devoted to the development of a finite element model that can predict primary to secondary and tertiary stresses induced at the areas of interest. There are two aspects to this problem: one is that the finite element mesh must be fine enough to capture tertiary stresses induced by the combined ingress water–bulk cargo in flooded hold No. 1 and external water pressure. The second aspect is that the boundary conditions must be such as to correctly approach the girder bending of
the ship at the area of interest and allow for the prediction of primary and secondary stresses. The approach presented has the advantage that the whole model of the ship and submodelling/substructuring techniques [3], [6] are not required. Results from the structural analyses performed using this model are presented and discussed. The main purpose of nonlinear analyses performed is to assess the adequacy of IACS [1] rules on the scantling calculations of the corrugated bulkhead and the double bottom of hold No. 1 by a first principles approach, considering the provisions of SOLAS Chapter XII [2] for existing bulk carriers, given the fact that relevant historical data are quite rare. These structural areas are of particular interest in the framework of the present study, since SOLAS Chapter XII Regulation 6 mandates that the transverse watertight bulkhead between the two foremost holds as well as the double bottom of the foremost hold shall have sufficient strength to withstand flooding of the first hold. This regulation applies to all single side bulk carriers of 150 m in length and upwards constructed before 1 July 1999 and IACS provides rules for the construction of these areas in order to comply with SOLAS Chapter XII.

2. Selected vessel

The vessel selected as a base for the present finite element analysis has been built in 1998 by a major Korean yard for a Greek shipping company. Built before 1 July 1999 it is affected by the above-mentioned SOLAS Chapter XII Regulation 6 as ‘existing ship’. It is a contemporary single-skin (SS) design, incorporating all modern design trends for this type of vessel. The main particulars of the vessels are summarised in Table 1.

The size of the selected vessel is justified by the fact that it is a very usual bulk carrier design placed between the existing bulk carriers’ size extremes (cape and handy size), thus better allowing the generalisation of any obtained results from this work. In general terms, the ship is longitudinally stiffened except from the side shell between the hopper tank and the top-side tank that are transversely stiffened. The transverse frame spacing is 830 mm while the longitudinal stiffener spacing is 835 mm, except from specific locations. Also, in some areas, such as between the centreplane and the first longitudinal girder in the double bottom, transverse stiffeners are located at half web spacing.

Table 1
Main particulars of the vessel under consideration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length OA (m)</td>
<td>224</td>
</tr>
<tr>
<td>Breadth (m)</td>
<td>32.24</td>
</tr>
<tr>
<td>Depth (m)</td>
<td>19.1</td>
</tr>
<tr>
<td>LS weight (t)</td>
<td>11,100</td>
</tr>
<tr>
<td>Deadweight (t)</td>
<td>72,700</td>
</tr>
<tr>
<td>Number of holds</td>
<td>7</td>
</tr>
<tr>
<td>Type of vessel</td>
<td>PANAMAX single-skin construction</td>
</tr>
<tr>
<td>Class</td>
<td>Lloyd’s register of shipping</td>
</tr>
</tbody>
</table>
3. FE modelling aspects

The primary concern for the finite element model developed is to generate a model that would give best possible predictions of the structural strength, even at the level of secondary and tertiary stresses at the bulkhead and double bottom. These stresses are developed as a result of the pressure exerted by the cargo and ingress water in hold No. 1, when flooded, and the pressure exerted by the surrounding seawater. In addition, the modelled boundary conditions, as described in Paragraph 6, should allow for the estimation of primary stresses. Based on these assumptions and the fact that very fine meshes are required to estimate tertiary stresses, a reasonable modelling extend ranges from halfway hold No. 2 up to halfway hold No. 1 lengthwise and up to the centreplane transverse wise.

The FE code used for the analysis is ABAQUS/Standard [4]. This is a widely used commercial finite element code for structural and other analyses. This code was preferred, because it is versatile, provides an extensive library of elements and several options for nonlinear solutions. The shell elements used for the modelling are four-node quadrilaterals and three-node triangulars. Four-node elements use a full integration scheme based on a variation of the Assumed Strain Method. They are intensively tested in the past for their accuracy and convergence, in both linear and nonlinear applications. Three-node elements use the reduced integration scheme since they predict thick shell behaviour more accurately than fully integrated triangulars. Extensive shape tests were performed on all elements used in order to ensure their conformity with specific geometric constraints. These tests are essential for an accurate prediction of node displacements and stress/strain convergence.

In order to define the mesh density that should be used to predict tertiary stresses, convergence studies were carried out. These studies revealed that at least 11 elements are needed along the breadth of each plate of the corrugation and at least eight elements along the smallest spacing between stiffeners. Web frames, transverses and longitudinal stiffeners are modelled with at least three elements along the height of the web and at least two elements along the width of the flange. Structural details such as manholes, brackets, tripping brackets and minor strengthenings to avoid buckling are included in the model. Such details are essential for the smooth stress flow in linear analyses but also for nonlinear analyses, where local plastifications and buckling due to stress concentrations may cause the analysis to stop before nonlinearities occur at the areas of interest.

Such a modelling results to very fine meshes: the final model includes approximately 350,000 nodes and 350,000 shell elements. Fig. 1 shows an outline view of the finished model. It should be mentioned that all figures presented in the following, show only parts of the finite element mesh. Nevertheless, since the mesh is very dense, it is very difficult to show entire large structures where all element edges are visible. Therefore, many figures show rendered or transparent parts of the structure for better comprehension. It can be noticed in Fig. 1 that the FE model is developed following the actual hull shape of the ship. Since the foremost bulkhead is herein of particular interest, it is important that the actual shape of the ship is used. This might slightly affect the generality of the obtained results for other bulk carrier
types and a parallel model could have been used instead, as an alternative, in order not to limit the results to the particular ship. However, because one the aim of the present study is to assess the adequacy of pertinent IACS rules for the provisions of SOLAS Chapter XII and the identification of local structural weaknesses in an actual design, all scantlings were accounted for the geometry and the specific ship under consideration, since a simplification of the hull form would render the model unrealistic.

The model consists of the following major parts:

- double bottom,
- bottom-side tank (hopper tank),
- side shell,
- top-side tank,
- transverse bulkhead,
- deck and hatches.
The transverse bulkhead consists of the following parts:

- lower stool,
- upper stool,
- corrugations.

4. Model description

In the following a brief description of the finite element model is provided. The geometry design and meshing operations are all carried out using the MSC/PATRAN pre- and post-processor. This program provides general tools for geometric and finite element modelling but no ship-specific tools. It is nevertheless preferred because of its generality and the mesh quality produced.

The two stools (Fig. 2) are box-like structures on which the corrugations (Fig. 2) are actually attached. The lower stool is in general much more rigid than the upper stool. The two corrugations close to the side of the ship, at their upper part, are attached to the top-side tank (Fig. 3). Large brackets are used to smoothen the transition between the horizontal upper stool and the top-side tank.

![Fig. 2. View of the corrugated bulkhead—mesh detail of the corrugation, stool and slant plate.](image-url)
Fig. 3 shows the connection areas between the corrugations, the stools and the two side tanks. It may be seen that the corrugations are cut horizontally at their upper part, while their lower part is inclined in order to be attached to the upper part of the lower stool. Also, it may be seen that large inclined slant plates exist between the corrugations. As already stated the lower stool is more rigid compared to the upper stool. Fig. 4 shows the stiffeners inside the stool as well as the double bottom stiffeners directly underneath. Also, heavier intermediate longitudinal webs exist every three frames. At the upper stool a similar, but lighter, stiffening system is used. At this area, large webs extend fore and aft the upper stools that support the deck between consecutive hatch openings. These webs can be seen in Fig. 9.

The stiffening system of the double bottom and hopper tank may be seen in Fig. 5. Afore the bulkhead there is a watertight girder on the centreplane, which is longitudinally stiffened. In general, the fore part of the double bottom is much stiffer than the aft part. Longitudinal stiffeners are heavier and plate thickness larger. This is due to the fact that the double bottom is designed to withstand flooding of the hold.

Fig. 6 shows how the longitudinal stiffeners are traversing the web frame floors. This figure shows the respective structure inside the hopper tank, but similar configurations are used in all cases. It may be seen that there are brackets that support the longitudinals and the floor stiffeners as well as special tripping brackets when the longitudinals are traversing close to the opening.

The side shell and stiffeners may be seen in Fig. 7. The transverse stiffeners are $420 \times 15/170 \times 16$ T-section profiles. This is the only area of the ship where purely transverse stiffening is used. Three frames afore the transverse bulkhead, there exists a trunk which is one frame-spacing wide. Transverse stiffeners are wider at their upper and lower end where they are attached to the top and hopper tanks.
Fig. 4. Stiffening of the lower stool and double bottom.

Fig. 5. Double bottom and hopper tank stiffeners.
Fig. 6. Hopper tank web floors and stiffeners.

Fig. 7. Side shell and stiffeners.
Fig. 8 shows the top-side tank transverse frames and longitudinal stiffeners. It can be noticed that two transverse webs are longer than the others. These are the boundaries of the hatch openings and are elongated in order to support the deck, hatch and longitudinal webs. These structures can be seen in Fig. 9, as well as the deck transverse stiffeners.

Fig. 10 shows the deck and hatch configuration. Large vertical brackets support the hatches. A large stiffener traverses the top of the hatch while smaller stiffeners also exist. A thin flatbar may also be seen at the inside of the hatch opening.

5. Materials

Three kinds of steel are used for the ship under consideration. All materials are in accordance with the requirements of Lloyd’s Register, under which the ship is classified. The materials considered are:

Mild steel Grade “A”: Elasticity modulus 201 GPa, yield stress 235 MPa, maximum stress 400 MPa and maximum plastic strain 0.22.

Higher tensile steel “AH” Grade “A”: Elasticity modulus 201 GPa, yield stress 315 MPa, maximum stress 440 MPa and maximum plastic strain 0.22.
Higher tensile steel “AH36” Grade “A”: Elasticity modulus 201 GPa, yield stress 355 MPa, maximum stress 490 MPa and maximum plastic strain 0.21.

For all kinds of steel used, the Poisson ratio is considered to be 0.3 and the density 7850 kg/m³.
6. Boundary conditions

One of the most serious tasks related to the proper modelling of ship structures using finite elements is the definition of the boundary conditions. Especially in the case of modelling entire parts of ships, incorrect boundary conditions may introduce considerable errors by suppressing the deformation of the cross sections at which they are applied or by giving rise to deformation modes that are not realistic. For the particular model of the present PANAMAX bulk carrier, the following boundary conditions have been used.

Since the cargo and sea pressure is symmetric with reference to the centreplane, there is no difficulty in applying symmetry boundary conditions at the centreplane. Thus, all nodes on the centreplane cannot translate transversely and rotate around the vertical and longitudinal axis.

The major problem lies with the boundary conditions for the aft and fore transverse sections. These sections lie almost in the middle of holds 2 and 1, respectively. This means that for each hold, symmetry should be accounted for. Also, the whole transverse section could distort and nodes on this section should in general be free to translate on the section’s plane. Further, in order to predict primary stresses using the finite element model, the boundary conditions should be such as to induce nodal forces and moments that when summed, to correspond to the hull girder shearing forces and bending moments. Fig. 11 shows the shear force and bending moment curves for the particular ship and loading condition. Such a plot may be considered typical for an alternately loaded bulk carrier. Vertical black lines show the locations of the bulkheads. Such plots are quite typical for the particular loading condition, which gives the most unfavourable loading condition on the bulkhead of hold 1 in case of flooding. It is easily noticed that between two consecutive bulkheads there is a location where the shearing force is zero. It may be seen that approximately in the middle of hold 2 (fr190–fr220) there is such a point,
where the shear force is zero and the bending moment curve has a local maximum. On the other hand, due to the very small shearing force at the collision bulkhead, there is a location where the bending moment is zero within hold 1 (fr220–fr250). These two points have been observed in other designs too, so it may be said that for a bulk carrier at this loading condition, there is a point within hold 2 where the shearing force is zero and a point within hold 1 where the bending moment is zero. These forces and moments are induced to a beam using the boundary conditions presented in Fig. 12.

The beam in Fig. 12 is isostatic. The boundary condition on the left allows the section to translate vertically but not to translate horizontally or rotate; thus, a bending moment is the reaction at this end. The boundary condition on the right allows the section to translate horizontally and to rotate but not to translate vertically. Thus, the reaction is a shearing force. These reactions correspond directly to the bending moment and shearing force in holds 2 and 1, respectively, as observed earlier, and are in equilibrium with the distributed load (pressure) at these holds. If such boundary conditions are applied to the finite element model, primary stresses due to hull girder bending are predicted, along with secondary and tertiary stresses. These boundary conditions correspond to constraining the horizontal translation of the nodes of the aft section and the vertical translation of the nodes of the fore section of the finite element model. In addition, transverse and vertical rotations of the nodes at the aft and fore sections are also constrained to account for the symmetry at the stiffened plate level. These boundary conditions have been tested for their adequacy during the preliminary runs. The cargo and sea pressure specified for the alternate loading condition has been used along with these boundary conditions and the shearing force obtained for the fore section is the same as the one specified by the shearing force curve with remarkable precision. In the case of flooding of hold 1, these two points may change, but one may easily find such points using the damaged condition shearing force and bending moment curves. It should be mentioned that in order to minimise the effect of boundary conditions on the stress field, the transverse section selected for and aft as a boundary section is a web frame.

![Fig. 12. Beam representing the loading condition and boundary conditions for holds 1 and 2.](image)
7. Loads

The loads applied are defined in such a way as to examine that an actual structure constructed according to the regulations for the first hold may withstand the combined ingression water and load pressure. According to UR S19 this combined pressure on the corrugations is given according to the following calculations.

In Fig. 13 the flooding head $h_f$ is the distance (m) measured vertically with the ship in the upright position, from the calculation point P to a level located at a distance $d_f$ (m) from the baseline. For the particular vessel $d_f$ is taken equal to $D$, the distance (m) from the baseline to the freeboard deck at side amidships. While $d_f$ is the flooding head measured from the baseline, $d_1$ is the distance (m) from the baseline up to the level where there is both cargo and ingression water. In Fig. 13, the thick curve denotes the cargo configuration before flooding and the hatched area the cargo configuration after flooding. The distance $d_1$ is calculated by the following equation:

$$d_1 = \frac{M_c}{\rho \lambda_c B} + \frac{v_{LS}}{I_c B} + (h_{HT} - h_{DB}) \frac{h_{HT}}{B} + h_{DB}.$$  \hspace{1cm} (1)

Because $d_f > d_1$ the following equations are used to give the pressure on the corrugations (Table 2).

At each point of the bulkhead located between $d_1$ and $d_f$ from the baseline, the pressure $p_c, f$ (kN/m$^2$) is given by

$$p_{c, f} = \rho gh_f.$$  \hspace{1cm} (2)

Fig. 13. Transverse section of a bulk carrier in the flooded condition.
At each point of the bulkhead located at a distance lower than \( d_{1} \) from the baseline, the pressure \( p_{c,f} \) (kN/m\(^2\)) is given by

\[
p_{c,f} = \rho g h_{f} + [\rho_{c} - \rho(1 - \text{perm})]g h_{1} \tan^{2} \gamma.
\] (3)

Eq. (3) applies for the corrugations of the bulkhead, which are normal to the horizontal plane (or other vertical surfaces, such as the side shell). For other surfaces such as the lower stool, the hopper tank top and the inner bottom, this formula may be generalised (Table 3):

\[
p_{c,f} = \rho g h_{f} + [\rho_{c} - \rho(1 - \text{perm})]g h_{1}[\sin^{2} x \tan^{2} \gamma + \cos^{2} x],
\] (4)

where \( x \) is the angle (degrees) between the horizontal plane and the surface of the hull structure to which the calculation point belongs.

In the UR S19 calculations, it is implicitly considered that the level of cargo after flooding, \( d_{1} \), is calculated for a hold that has parallel sides. The pressure distribution of the cargo alone that is calculated using these formulas, if summed, gives a total

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**Table 2**

Summarises the calculations for \( d_{1} \) and nomenclature

<table>
<thead>
<tr>
<th>Df (m)</th>
<th>19.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass of cargo in hold No. 1, ( M_{c} ) (t)</td>
<td>14,318.8</td>
</tr>
<tr>
<td>Bulk cargo density, ( \rho_{c} ) (t/m(^3))</td>
<td>3</td>
</tr>
<tr>
<td>Length of hold No. 1, ( l_{c} ) (m)</td>
<td>24.9</td>
</tr>
<tr>
<td>Ship’s breadth amidships, ( B ) (m)</td>
<td>32.24</td>
</tr>
<tr>
<td>Volume of bottom stool above the inner bottom, ( v_{1,5} ) (m(^3))</td>
<td>139.5</td>
</tr>
<tr>
<td>Height of the hopper tanks amidships from the baseline, ( h_{HT} ) (m)</td>
<td>6</td>
</tr>
<tr>
<td>Height of the double bottom, ( h_{DB} ) (m)</td>
<td>1.8</td>
</tr>
<tr>
<td>Breadth of the hopper tanks amidships, ( b_{HT} ) (m)</td>
<td>4.43</td>
</tr>
<tr>
<td>( d_{1} ) (m)</td>
<td>8.49642</td>
</tr>
</tbody>
</table>

*Note: The bulk cargo density \( \rho_{c} \) is for iron ore.*

**Table 3**

Summarises the calculations for \( p_{c,f} \) and nomenclature

<table>
<thead>
<tr>
<th>Water density, ( \rho ) (t/m(^3))</th>
<th>1.024</th>
</tr>
</thead>
<tbody>
<tr>
<td>( g ) (m/s(^2))</td>
<td>9.81</td>
</tr>
<tr>
<td>permeability, perm (t/m(^3))</td>
<td>0.3</td>
</tr>
<tr>
<td>Angle of repose of the cargo, ( \phi ) (deg)</td>
<td>35</td>
</tr>
<tr>
<td>( \gamma = 45^\circ - (\phi/2) ) (deg)</td>
<td>27.5</td>
</tr>
<tr>
<td>( \tan^{2}\gamma )</td>
<td>0.27099</td>
</tr>
<tr>
<td>( p_{c,f} ) at ( h_{DB} ) (kN/m(^2))</td>
<td>214.431</td>
</tr>
<tr>
<td>( p_{c,f} ) at ( d_{1} ) (kN/m(^2))</td>
<td>106.517</td>
</tr>
</tbody>
</table>

*Note: The cargo permeability (perm) is for ore, \( h_{1} \) is the vertical distance (m) from the calculation point to a level located at distance \( d_{1} \), as defined above, from the baseline (Fig. A.15). Angle of repose of cargo \( \phi \) is for iron ore.*
cargo weight that is approximately 30% smaller than the actual cargo for the particular vessel. This is due to the fact that the sides of the first hold are not parallel, so \( d_1 \) is underestimated. Exact calculations for hold 1 have shown that the actual \( d_1 \) would be 10.734 m instead of 8.496 m. This difference slightly moves the knuckle point of the pressure distribution towards the deck (Fig. 14).

The difference in pressure at the corrugations is not significant, but for the inner bottom it is about 15% greater. For this reason, two sets of runs are performed for the finite element model: one set that accounts for the pressure distribution as calculated using UR S19 in order to determine if an actual structure may indeed withstand the calculations’ pressure, and one set that accounts for the modified pressure, to determine if the structure may withstand the actual load exerted when hold 1 is flooded. It is also examined if this difference yields significantly different results. For comparison, the following two tables show the calculated pressure values for the two different cases at various locations (Tables 4 and 5).

For the flooded condition, it is considered that the draught is the same as the water level inside hold 1 and no trim has been included. The calculations for the ambient

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**Fig. 14.** S19 vs. modified pressure on bulkhead.

**Table 4**
Calculations for \( p_{cf} \) according to UR S19

<table>
<thead>
<tr>
<th>Calculation point location (m)</th>
<th>( \varphi = 90^\circ ) (corrugations, etc.) (kPa)</th>
<th>( \varphi = 70^\circ ) (lower stool, etc.) (kPa)</th>
<th>( \varphi = 45^\circ ) (hopper tank, etc.) (kPa)</th>
<th>Inner bottom (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.8</td>
<td>214.431</td>
<td>227.222</td>
<td>269.103</td>
<td>323.774</td>
</tr>
<tr>
<td>8.496</td>
<td>106.518</td>
<td>106.518</td>
<td>106.518</td>
<td></td>
</tr>
<tr>
<td>19.1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
sea pressure are based on these assumptions. Gravity is also included in order to account for the weight of the steel structure.

8. Types of analyses—computing runs

In the course of the present work, several preliminary analyses were carried out as a preparatory step towards the verification of the modelling, loading and boundary conditions. These preliminary analyses were all linear elastic. Computing time required for each of these preparatory analyses was about 3.30 h on an Intel 866 MHz workstation with 768MB RAM running Windows 2000. The detailed analyses performed at the next stage for obtaining the results presented hereafter were nonlinear static, accounting for both material and geometric nonlinearities. Relevant computing runs performed for the assessment of the pressure specified by UR S19 took about 4.5 days and an average of eight increments was needed for each step. Approximately 30GB of disk space were needed for scratch and result files storage. For each increment, especially for the last ones, many iterations where required to reach acceptable convergence. It should be mentioned that all cases, for which results are presented, correspond to the actual load exerted on the structure and not to the ultimate load for which convergence may be reached, the latter indicating the presence of severe mechanisms due to extensive plastification or buckling.

9. Results for the pressure specified by UR S19

In this section, results for the pressure level prescribed by UR S19 are presented. These results are in general von Mises stress plots on the finite elements for particular parts of the structure. To the right of each figure there is a coloured scale, which corresponds to the stress levels plotted on the structure sketch. Unless otherwise noted, the stresses presented in each figure correspond to 100% of the applied pressure. The stress and strain results presented correspond to the layer that exhibits the highest stress. It should also be mentioned that the distortion of the structure is exaggerated for visualisation purposes.

### Table 5
Calculations for \( p_{cf} \) for the actual value of \( d_1 \)

<table>
<thead>
<tr>
<th>Calculation point location (m)</th>
<th>( a = 90^\circ ) (corrugations, etc.) (kPa)</th>
<th>( a = 70^\circ ) (lower stool, etc.) (kPa)</th>
<th>( a = 45^\circ ) (hopper tank, etc.) (kPa)</th>
<th>Inner bottom (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.8</td>
<td>228.010</td>
<td>245.074</td>
<td>300.947</td>
<td>373.883</td>
</tr>
<tr>
<td>10.734</td>
<td>84.044</td>
<td>84.044</td>
<td>84.044</td>
<td>84.044</td>
</tr>
<tr>
<td>19.1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
In general, it may be noticed that the boundary conditions perform quite well, as there is no visible effect on the stress field (Figs. 15 and 16). At the inner bottom for example, the stress distribution is uniform and not affected by the boundary conditions. Also, there are no stress concentrations at nodes where constraints are applied.

In Fig. 15, it can be noticed that the upper stool and upper part of the bulkhead are practically stress-free, since at these areas very small pressures are applied. It is also worth noticing that small stresses occur on the bulkhead and that the inner bottom in hold 1 mostly suffers from tertiary stresses between stiffeners. The latter is more evident in Fig. 16: the double bottom in hold 2 is significantly bent while the double bottom in hold 1 is inclined. In hold 2, the excessive bending is due to the fact that the hold is empty and only the water pressure is applied at the bottom. Further, a large bending moment is exerted at its aft end, since it is not allowed to rotate. On the other hand, in hold 1 only a shear force is applied at its fore end, and the cargo and sea pressures are partially counterbalanced. This is why there are high stresses at the girder in hold 2 while the girder in hold 1 is practically stress-free.

The secondary bending of the double bottom in hold 2 may form a potential hazard to the safety of the ship, in case of flooding of hold 1. Fig. 17 shows that high stresses occur at the girders and especially close to their upper intersection with the
watertight floor. These stresses are about 317 MPa, slightly higher than the yield stress (315 MPa), and the corresponding strains are about 3.71e−3, but quite smaller than the maximum plastic strain (0.22). These stresses are mainly caused by excessive in-plane shear and compressive normal stresses. The maximum stress in Fig. 17 occurs at one of the manholes and may be due to a design problem. These stresses are mainly caused by normal stresses due to the bending of the girders.

Another area of high stresses is the bottom of hold 2. The plating at the bottom of this area (Fig. 18) suffers high secondary and tertiary stresses and at some points these stresses are higher than the yield stress (315 MPa) but still strains are quite small. It is interesting to notice in Fig. 18 that high stresses, though elastic, occur at the side shell of hold 1. These stresses are mainly shear stresses.

In general, stresses at the plating, girders and floors of the double bottom of hold 1 (Fig. 19) are quite small and well below the yield point. Limited plastifications occur only at the stiffeners of the inner bottom close to their intersections with the bottom floor. This floor lies directly underneath the edge of the lower stool, which behaves as a rigid box. The rigid stool rotates around the transverse axis due to the lateral load on the bulkhead and stool. This leads to local stressing of the stiffeners attached to the floor.

As far as the bulkhead is considered, stresses are below the yield stress, which in general is 315 MPa at this area (Fig. 20). The only point at which stresses are very
close to the yield stress is at the centreplane girder, right underneath the bulkhead, due to compressive stresses. It should be mentioned that at the centreline elevation and abaft the bulkhead location there are only longitudinal stiffeners, which support the duct keel. Afore the bulkhead location there is no duct keel and at that elevation there is a girder. In order to smoothly transition from the stiffeners to the girder there are two large brackets supporting the stiffeners. The maximum of the stress at this area occurs on the upper bracket. At the front of the lower stool there is a discontinuity in the stress field: namely, stresses at the lower part of the stool plating are larger than those at the upper part. This is due to the fact that the lower plating of the stool is 15 mm thick, quite smaller compared to that of the upper part where the plating is 18.5 mm thick. In general, there are no other points where high stresses occur. Some stress concentrations occur, as expected, at the intersection of the slant plate with the corrugation and between the corrugation and the lower stool plating. Also, the lower stool plating and diaphragm are affected by the hard point at the intersection of the first double bottom girder with the watertight floor. Nevertheless, all these stresses are lower than the yield stress.

Figs. 21 and 22 show the isostress contours on the corrugation. It may be seen that the stresses are higher at the lower part of the corrugation and are concentrated at the hard points mentioned earlier. Also, stress concentrations at the knuckles of the corrugation are also visible.
10. Results for the pressure calculated for the actual cargo

As expected, the results for the load pressure distribution calculated taking into account the actual level of cargo inside hold 1, does not introduce any considerable changes in the stress and strain distributions. The stresses at the areas of interest are quite similar to the ones presented in the previous case. The maximum of the equivalent stress occurs at a manhole at the front of the girder in the double bottom of hold 1.

Figs. 23–25 present a series of normal stress results at three different horizontal sections of the middle half corrugation of the bulkhead: one at the top of the bulkhead, where it connects to the upper stool, one at the middle of the corrugation and one at the bottom of the bulkhead, at the location where the corrugation and the slant plate intersect. These stress patterns are quite typical for corrugated bulkheads. These plots show that normal stresses are very small at the top of the corrugation and, in the load case accounting for the actual load level, slightly higher than for the UR S19 pressure. At the middle of the corrugation, stresses are higher and the effect of the stress concentration at the fold lines is evident. In this case, the stresses are practically the same for the two cases. At the bottom of the corrugation, the maximum normal stresses appear. At most locations, they are about 10% larger in the second load case. It is also evident in both cases that at the lower flange, where it intersects with the slant plate, the stresses are almost uniform and compressive.
Fig. 19. Stresses at the double bottom hold 1.

Fig. 20. Stresses at the corrugation, stools and double bottom closest to the centreplane.
11. Conclusions

A nonlinear analysis accounting for both material and geometric nonlinearities has been performed with a developed finite element model regarding hold No. 1 of a PANAMAX type. SS bulk carrier.

Two specific load cases were herein considered, namely:

- one accounting for the load pressure in hold 1 as prescribed by UR S19 and
- one corresponding to the load of the actual level of cargo inside the hold.

In general, the scantlings of the bulkhead and double bottom of hold 1 of the present design can be considered adequate since there appear no critical stresses. In general, it appears that the double bottom in hold 2 suffers larger stresses that could herein become critical, since it is severely bent due to the absence of cargo inside hold

![Fig. 21. Isostress contours at the corrugation.](image-url)
2. High stress concentrations occur at the intersection of the girders of the double bottom in hold 2 with the watertight floor and stool. This is caused by the secondary bending of the double bottom in hold 2. It appears interesting to investigate if this stress concentration is caused by the right-angled configuration of the stool in hold 2 of the present design and if the fitting of a symmetric stool, that is, inclined in both...

![Isostress contours at the corrugation.](image)

![Normal stresses at the top of the corrugation.](image)

(a) Normal stress results for the pressure prescribed by UR S19. (b) Normal stress results for the pressure calculated for the actual cargo.
holds, could smoothen the stress flow at this area. Also, more detailed models have to be used when estimating stresses at this “hot-spot” accurately. Large plastic stresses occur at the bottom plating that may lead to rupture of the skin at this area.

Another location where high stresses occur at the present design is the inner bottom stiffeners in hold 1 at their intersection with the floor. This is also an area of high stress concentrations and should be investigated using more dense meshes.

The previous observations on the induced stresses at the areas of interest show that the scantlings of a ship constructed according to IACS rules are adequate to withstand the design loads. Nevertheless, scantling calculations assume that the loads are applied statically, which may not be the case if sloshing occurs inside the

Fig. 24. Normal stresses at the mid of the corrugation. All stresses in MPa. (a) Normal stress results for the pressure prescribed by UR S19. (b) Normal stress results for the pressure calculated for the actual cargo.

Fig. 25. Normal stresses at the bottom of the corrugation. All stresses in MPa. (a) Normal stress results for the pressure prescribed by UR S19. (b) Normal stress results for the pressure calculated for the actual cargo.
hold. Future work on this subject should account for this possibility and scale factors could be evaluated and incorporated to the rules.

In view of the above findings identifying the ‘hot spots’ in the forward structure of the analysed SS bulk carrier, mainly in parts of the double bottom and transverse bulkhead areas and comparing to the situation of a comparable double skin (DS) bulk carrier design [7], the main difference of which, to the present SS design, is the introduction of properly stiffened, side bulkheads at a specific distance from the outer shell1 [5,8], reducing the inherent risk of cargo hold flooding through breaching of the outer shell, it is concluded that critical structural spots in the forward structure of a DS bulk carrier cannot differ significantly from those already identified for the SS bulk carrier designs, and therefore the possible extension of the application of the provisions of SOLAS Chapter XII to DS bulk carriers appears straightforward. Note that until now and in view of the lack of historical accident data, indicating the need for a different approach, no special classification society rules were issued to cover possible differences between SS and DS designs, though it is expected that relevant standard DS bulk carrier designs of major shipbuilders are commonly cross checked by proper FE models both on the builder’s and the classification society’s side. It is beyond the scope of the present study to recommend a possible change of policy of the classification societies and the issuance of specific rules for DS bulk carriers.

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References

[2] SOLAS. Amendments to the annex to the International Convention for the safety of Life at Sea. SOLAS, 1974 [Chapter XII].

1 This distance might vary between 0.76 and 1.0 m, according to KRS (Application of Formal Safety Assessment Methodology to No. 1 cargo hold Flooding of Bulk Carriers, issued by Korean register of Shipping, MSC 72, May 2000).


[8] MSC72/INF. Application of formal safety assessment methodology to No. 1 cargo hold flooding of bulk carriers, submitted by the Korean Register of Shipping to the IPSB, May 2000.