EFFECT OF DOUBLE BOTTOM HEIGHT ON THE STRUCTURAL BEHAVIOUR OF BULK CARRIERS

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P D Contraros, PDC Maritime & Theta Marine, UK
S P Phokas, Theta Marine, Greece

SUMMARY

This is the first of a series of companion papers that the authors propose to present on the effect that the new CSR Rules will have on the design of bulk carriers. Our initial focus will be on the new design framework established for the inner bottom height of such vessels, a parameter critical to their structural integrity. It examines the effect that double bottom height reduction has on the reliability of the bulk carrier structure, by applying a finite element 3D - 3 hold analysis of varying double bottom heights to a typical current Panamax bulk carrier design. The results are compared to pre and post IACS CSR[2] requirements. The conclusion reached is that the establishing of the double bottom height should not be left to direct calculations. A minimum acceptable height should be established in order to maintain a minimum level of structural reliability and safety.

NOMENCLATURE

CSR	Common Structural Rules
IACS	International Association of Classification Societies
UR	Unified Requirement
SH	ABS Safe Hull
V10	Version 10.0
FE	Finite Element
FEA	Finite Element Analysis
3D	3 Dimensional
CH	Cargo Hold
DWT	Deadweight (tonnes)
L	Scantling Length of the ship (m)
ℓ_{DB}	Length of the double bottom between Lower Stool's footings (m)
B	Moulded Breadth of the vessel (m)
D	Moulded Depth of the vessel (m)
B_{DB}	Breadth of the double bottom between bilge hoppers (m)
d_{DB} (*or H*)	Height of double bottom (mm)
d	Molded draught to the summer load line of the vessel (m)
BHT_W	Width of Bilge Hopper Tank (m)
TST_W	Width of Top Side Tank (m)
DB	Double Bottom
HTS 32 or 36	Higher Tensile Strength Steel (of Yield Point 3200 or 3600 kg/mm^2)
VM	Von Misses Stress (kg/mm^2)
t	Plate Thickness (mm)
DLA	Dynamic Loading Approach

1. INTRODUCTION

Bulk carriers are the workhorses of the merchant fleet, carrying a wide variety of cargoes. Cargoes that are not always stowed in the exact same locations as on container vessels, which do not have the same behaviour as the liquids of the tank vessels and with a wide range of stowage factors. Cargoes with specific gravities declared by the shippers (with a high degree of uncertainty), and which are loaded at exceptionally high rates controlled not by the vessel's master but by the terminal operators. Designing a robust bulk carrier is a demanding exercise. Due to the uncertainties previously stated, their designers should place considerable reliance on the experience gained from the operation of these vessels through the years. For the past 100 years this experience was traditionally reflected in the Class Rules. In the last 35 years it was in the form of explicit upper or lower limits for the scantlings and arrangements of their primary supporting members. In the development of the CSR Rules the IACS group on bulk carriers chose to rely heavily on FEA. Most of the previously set limits on the design and arrangement of primary supporting members of bulk carriers were lifted. Voluminous and valuable written contributions in support of these limits by bulk carrier operators, some of which have followed for years the everyday operations and problems of fleets larger than those of individual Societies, were set aside. The fact that operators' experience is based on every day follow up of this enormous fleet, while Class Surveyors board the vessels a limited number of times each year was not considered. Rising demand for increased cargo volume and deadweight of bulk carriers has led designers to increase the depth and draught of current vessels. Shipyards followed by increasing use of higher tensile strength steel to almost 100%. The introduction of computer aided design allowed designers to eliminate margins inherent in the traditional Class Rules, and the new design optimization philosophy of "carry cargo and not steel" led to an unacceptable number of casualties and ship losses in the 80s and early 90s. IMO's intervention resulted in a number of retroactive IACS UR's, which were applied at the expense of the owners. The introduction of the CSR by IACS has created a new design philosophy that permits greater flexibility to designers, and supports the modern trend of increasing the vessel's carrying capacity without increasing its breadth or length. This has resulted in ship designs with reduced double bottom heights and cross sections of the lower and upper side tanks (see Figure 1).

2. SELECTION OF THE TYPE OF BULK CARRIER TO BE INVESTIGATED

Bulk carriers are defined in IACS UR Z11.2.2 [1] as self propelled ships which are constructed generally with single deck, double bottom, hopper side tanks, top side tanks, with single or double side skin construction in the cargo length area, and intended to carry dry cargoes in bulk. Commonly carried cargoes today are bulk ore, coal, light cargoes, (commodities such as grain, wheat, soya beans, sugar etc.), steel products, log, chip and lumber and a number of other not so bulk type cargoes. Given that bulk carrier design is market driven, increased demands from developing countries in the last few years had a considerable effect on the design of bulk carriers of all types, and their sizes / capacities.

In general current bulk carriers fall into the following categories:

- Handy bulk carriers that are less than 40,000 DWT having 5 or less cargo holds with B less than 32.2 m

- Handymax and Supramax bulk carriers with 5 Cargo Holds, between 40,000–60,000 DWT, having L between 170.0 m–190.0 m and B at 32.2 m

- Panamax bulk carriers with DWT between 60,000 to 80,000 DWT, and Kamsharmax bulk carriers between 80,000 and 90,000 DWT, usually with 7 cargo holds and $B \geq 32.2$ m

- Cape size bulk carriers between 100,000–180,000 tons with 9 cargo holds, and B well over 32.2 m

For this investigation a Panamax bulk carrier was chosen, due to design failures suffered by a number of newly built vessels of this size. It also represents the current middle range of the fleet and is the size on which the Baltic Dry Freight rate is based.

3. EVOLUTION OF PRE AND POST CSR OF IACS CLASS SOCIETIES' REQUIREMENTS ON DOUBLE BOTTOM HEIGHT

IACS Class Rules for bulk carriers provide parametric equations for the calculation of the major ship parameters such as the double bottom height, and spacing of DB girders and floors. These requirements formed the lower limit for the design of any bulk carrier. In the 80s and early 90s these were followed by a FEA in order to verify and refine the results of the parametric equations, and locate specific areas in need of additional reinforcement. These limits were first introduced to provide adequate safety margins, and compensate for the uncertainties involved in the rule loadings. The minimalistic / fragmented FEA covered only the cargo holds located at 0.4L amidships[1], the computer power dependent FE modeling and other general input such as boundary conditions, unsymmetrical loading that could not be applied accurately on the model, size and type of elements, etc. It was clearly understood at that time that the FEA was indeed a strong mathematical tool but one which possessed neither convergence nor uniqueness of solutions. As such, it should be used with extreme care by entities that possess a good understanding of the structure analyzed and its expected behavior. It is not safe to consider that FEA reflects the absolute truth.

Table 1 shows the evolution of the bulk carrier double bottom design from early 70s until today as compared with pre and post CSR philosophies, together with the results of the new formula proposed by the authors. Evidently the new designs were developed to produce bulk carriers with reduced double bottom height, reduced number of double bottom girders (widely spaced), and increased double bottom width due to the reduced width of the bilge hopper box girder tank [see Figure 1]. Given that the cargo hold's length has remained almost constant, this practice alters the width to length aspect ratio of the double bottom resulting in an appreciably reduced stiffness due to the reduced height of the double bottom.

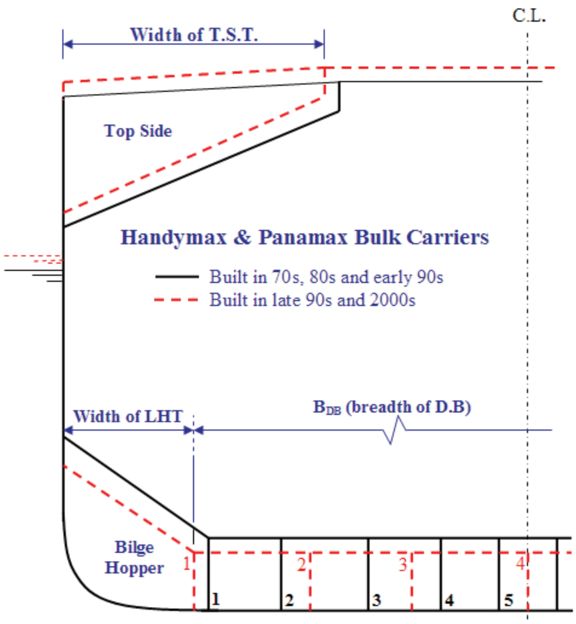

Figure 1: Typical schematic view of the evolution of the Handymax and Panamax bulk carriers built in 1970's until today (2000's)

For example, ABS Rules [3] prior to 1991, in paragraphs 23.1.3 & 7.3.2 required that the minimum double bottom height for vessels carrying heavy cargoes is to be as per the following equation.

$$d_{DB} = 32B + 190\sqrt{d}$$

[1] This practice could not of course handle and prevent failures such as the casualty of similar open type structure "MSC Napoli" [16]

Table 1: Evolution of the design of the double bottom structure of bulk carriers in operation (1970 until today) and a comparison with various current and past rules

	SIZE L_{scnt} x B x D (m) Year of Built	DWT (ton) d (m)	Width of LHT – TST (m)	DOUBLE BOTTOM HEIGHT – FLOOR SPACING – GIRDER SPACING (m)				
				As Built	IACS CSR	ABS Rules	DNV Rules	As Proposed Formulations
1.	Handy Size 174.7x27.0x15.5 1970s	35,100 10.9	3.20–7.20	1.64–1.60–2.70	1.35–3.20–4.00	1.49–3.00–3.00	1.47–1.87–1.87	1.60–2.40–3.00
2.	Handy Size 174.7x29.5x14.8 1980s	37,000 10.56	4.23–7.25	1.74–1.60–3.24	1.475–3.20–4.00	1.56–3.00–3.00	1.53–1.87–1.87	1.62–2.40–3.0/3.20
3.	Handy Size 188.5x23.7x15.3 1990s	34,600 10.65	4.03–4.78	1.69–2.40–3.90	1.185–3.20–4.00	1.37–3.00–3.00	1.36–1.93–1.93	1.40–2.40–3.0/3.20
4.	Handymax 172.13x27.6x17.0 1970s	40,200 12.00	4.20–8.30	1.725–1.60–2.40	1.38–3.20–4.00	1.54–3.00–3.00	1.53–1.85–1.85	1.55–2.40–3.00
5.	Handymax 178.96x32.24x16.9 1980s	47,800 10.59	3.72–8.52	1.80–2.25–3.10	1.61–3.20–4.00	1.65–3.00–3.00	1.62–1.88–1.88	1.79–2.40–3.00/3.20
6.	Handymax 175.50x30.40x16.5 1990s	45,000 11.60	3.20–7.20	1.81–2.40–4.00	1.52–3.20–4.00	1.62–3.00–3.00	1.61–1.87–1.87	1.77–2.40–3.00/3.20
7.	Handymax 179.5x32.26x16.7 Late 90s – 2000s	50,700 11.92	4.50–6.90	1.64–2.50–5.00	1.61–3.40–4.25	1.69–3.00–3.00	1.68–1.89–1.89	1.74–2.55–3.00/3.40
8.	Supramax 181.25x32.26x18.0 2000s	57,000 12.90	4.21–7.00	1.78–2.46–3.28	1.61–3.28–4.10	1.71–3.00–3.00	1.724–1.80–1.89	1.78–2.46–3.00/3.28
9.	Panamax 228.59x32.20x18.85 1970s	66,400 13.17	5.30–9.80	2.00–1.90–2.70	1.61–3.60–4.50	1.71–3.00–3.00	1.73–2.11–2.11	1.73–2.7–3.00/3.60
10.	Panamax 214.22x32.2x18.0 1980s	63,600 12.9	5.37–9.50	1.78–2.50–2.50	1.61–3.30–4.12	1.71–3.00–3.00	1.72–2.04–2.04	1.71–2.47–3.00/3.30
11.	Panamax 211.94x32.2x18.6 Late 1990s	72,000 13.44	4.76–8.81	1.68–2.55–4.05	1.61–3.24–4.05	1.72–3.00–3.00	1.74–2.03–2.03	1.77–2.43–3.00/3.24
12.	Panamax 213.79x32.2x19.15 2000s	75,000 13.82	4.76–8.81	1.68–2.58–4.05	1.61–3.40–4.25	1.74–3.00–3.00	1.76–2.04 – 2.04	1.77–2.55–3.00/3.40
13.	Cape Size 256.6x43.0x24.1 1990s	140,000 17.4	6.20–11.6	2.29–2.50–3.82	2.15–3.4–4.25	2.17–3.00–3.00	2.32–2.23 – 2.23	2.21–2.55–3.00/3.40
14.	Cape Size 273.54x45.0x24.1 Late 90s – 2000s	170,000 17.7	6.54–12.6	2.39–2.58–5.04	2.25–3.36–4.20	2.24–3.00–3.00	2.42–2.31–2.31	2.29–2.54–3.00/3.36

Additionally ABS Rules in paragraphs 23.15.1, 23.15.2 and 6.3.5 (c) dictate that both the spacing of the double bottom side girders and floors should be not less than 3 meters apart, thus essentially defining the bottom grillage properties.

DNV 1973 Rules [4] Chapter II Sec. 10/B301 required that the height of the center girder/double bottom is to be not less than:

$$H = (600 + 9\,B\sqrt{d}) \times 1.05 \text{ in mm}$$

which as per Ch III sec. 5/C304, it was to be increased by 5% for vessels carrying heavy cargoes.

Additionally, in line with the ABS philosophy, for the strength of the double bottom structure DNV Rules Chapter II section 5/C200 and C300 stipulated that the floors and side girders should be fitted with spacing not greater than:

$$\text{Spacing} \leq 4.5\,(L + 240)$$

IACS CSR 3/6.1.3 dictates that the height of double bottom be not less than:

DB Height = B/20 or 2 m whichever is less

CSR 3-6/6.3.3 states that the spacing of the bottom girders should generally be not greater than 4.6 m or 5 times the spacing of the bottom or inner bottom ordinary stiffeners, whichever is the smaller. CSR's 3-6/6.4.1 states that the spacing of the floor should not be greater than 3.5 m or 4 frame spaces whichever is the smaller. However, for both DB girders and floors greater spacing may be accepted, depending on the FEA results.

The CSR formula for the calculation of the DB Height is independent of the vessel's draught. This is quite strange given that this formula is applicable to all sizes of bulk carriers above 90 m in length, which have a wide range of draughts. It is quite unreasonable to size the depth of a grillage structure on a unidirectional span *(B),* ignoring the load that it is required to carry. The load and the grillage of the double bottom is a function of $f(d, B_{DB}, \ell_{DB})$.

The formulae for the requirements of double bottom height should include variables such as the draught of the new design which is the ship's principal dimension, to which the load applied on the double bottom is directly proportional. The length of the vessel controls the primary stress of the double bottom structure and the breadth of the double bottom structure controls the strength and stiffness of the double bottom in a transverse direction. In addition, Handymax & Supramax bulk carriers (most likely) have 5 cargo holds, Panamaxes have 7 cargo holds and Cape Sizes have 9 cargo holds, thus the length per hold is almost standard for most types of bulk carriers over 150 m in length. The following parametric equation was developed to fit the data indicated in Table 1 that compares well with the formulations given by other pre-CSR IACS Class Societies Rules:

$$d_{DB} = 45B_{DB} + 80\sqrt{d} + (L+240)$$

Where

d_{DB} = height of double bottom (mm)

B_{DB} = breadth of the double bottom between bilge hoppers (m) [as shown in above mentioned Figure 1]

d = molded draught to the summer load line of the vessel (m)

L = Scantling length of the vessel in m (as per Rule)

In combination with the following proposed requirements:

- The spacing of the adjacent girders is to be not greater than about 3.0m or 4 times the spacing of the bottom or inner bottom ordinary stiffeners, whichever is the smaller.
- The spacing of the floors is to be not greater than 3.0m or three (3) frame spaces, whichever is smaller.

The above proposed formulae and requirements were used to calculate the double bottom height (d_{DB}) and the spacing of floors and girders for the bulk carriers included in Table 1.

4. VESSEL'S STRUCTURAL ARRANGEMENTS

Given that the focus of this paper is the double bottom height, and since our decision was to use a Panamax bulk carrier for the model ship, we have selected a single sided vessel with a double bottom structure which reflects the current trend in the design of such vessels.

The midship section of the vessel is shown in Figure 2 (b) below. The vessel is longitudinally framed with transverse hold frames between the top side and hopper tanks. The transverse hold frames are spaced at 860 mm apart, with the inner bottom and outer bottom longitudinals spaced at 810 mm. The spacing of the deck longitudinals is 880 mm and the spacing of the side shell and top side slopped bulkhead longitudinals is 850 mm.

The materials are predominantly HTS 36 for the main deck and longitudinal members within the upper 3.0 m (measured from the main deck) and HTS 32 for the remaining longitudinal material, its inner bottom plating which is mild steel. Material used for the double bottom girders is HTS 36 at their end sections (under the stools and one bay between floors, located aft and fore of the stools). The remaining longitudinal materials of the bottom girders and floors are HTS 32. In summary, the whole double bottom structure was built with HTS 32 material apart from the inner bottom plating that was designed with mild steel and the ends of the double bottom girders that are designed with HTS 36 material.

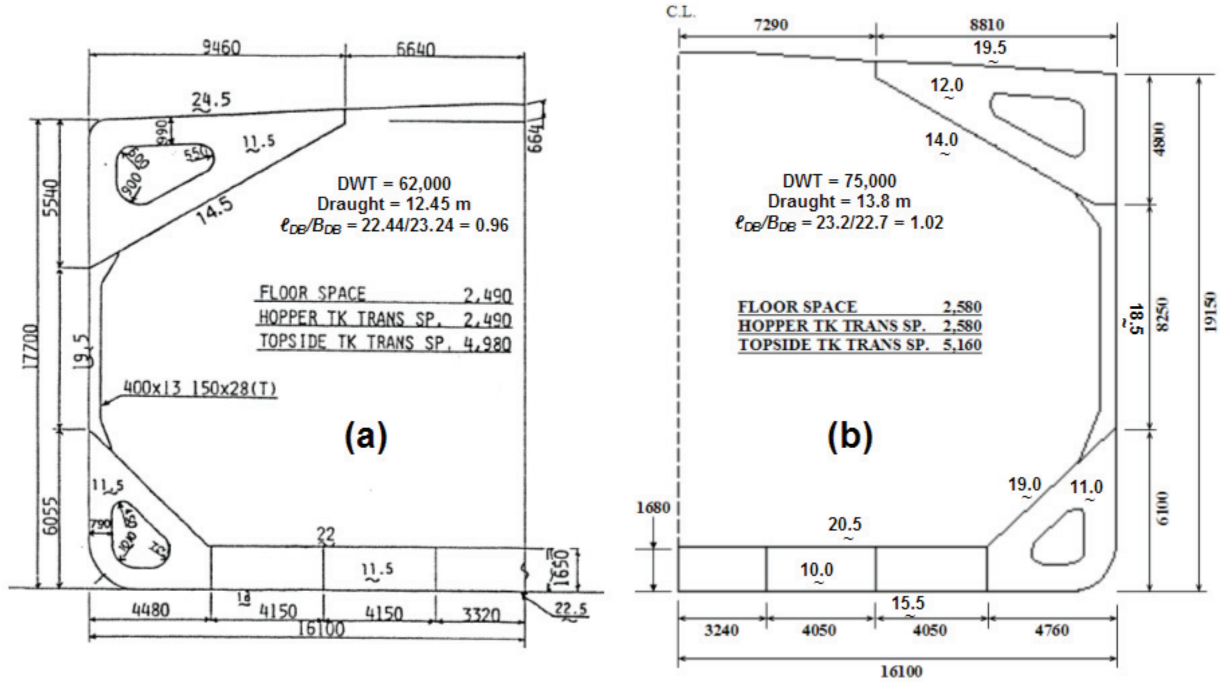

Figure 2: Midship Sections of the Ref. 14 Panamax ship of DWT 62,000[14](a) and basic Panamax ship of DWT 75,000 (b)

The ABS SafeHull[5] "net" scantling approach was used in FE model of the vessel where the minimum nominal design corrosion values are as shown in Figure 1 of part 5C Chapter 3 Section 2 of ABS 2009 Rules.

That means that the net scantlings were calculated by subtracting the nominal design corrosion values (NDCV) from the "as designed" scantlings.

5. FINITE ELEMENT 3D - 3 CARGO HOLD MODEL

ABS SafeHull V-10 was used for this study. The FE models consist of 3-cargo-hold-length of the midship structures, and are used to determine the global response of the hull girder and local behavior of the main supporting structures.

"One Step" FE method with combined (fine and coarse) mesh is used so that the simultaneous strength evaluation of both the hull girder and local structural members is achieved in one FE run. This method renders the local 2-D and / or 3-D fine mesh analysis redundant. If for instance, separate 2-D models were to be developed, the assumed boundary conditions, the omitted loads, moments and stresses in the 3rd dimension, result in detriment to the accuracy of the calculation. In short, the customary intermediate step that was usually followed by the designers / builders in order to reduce the computation effort by well over 60%, has been omitted.

The application of the "One Step" strategy is intended for the estimation of the overall scantlings of plates and stiffeners but also the structural details. The mesh sizes for the "One Step" FE models are generally close to one stiffener spacing (560 ~ 900 mm), except for areas found to be highly stressed. The latter areas were re-modeled after the initial run using finer mesh, whereby various locations of interest (highly stressed) including various openings and manholes can be assessed. Figure 8 below shows the resultant stresses around a manhole and pipe opening, and adjacent critical joints of the inner bottom to lower stool side plate versus the same girder without an opening.

The models developed reflect the whole cross-section (no symmetry boundary conditions about the center line used) of the vessel. No cutouts for longitudinal stiffeners and other small openings were modeled. Very fine mesh modeling that could induce also the hot spot stresses to critical areas (i.e. the end connections of the double bottom girders) were also included in the analysis.

Three basic prismatic models were used which reflect the structural behavior of the mid hold of each 3 hold model as shown in Figure 3.

Each FE model was modified and run separately. The modification involved alteration of the double bottom structure so as to correspond to five different double bottom heights. Figure 4 below, shows the FE model for the double bottom height of 1610 mm that is IACS CSR minimum value, 1680 mm (basic ship) and additional heights of 1800, 1900 and 2000 mm.

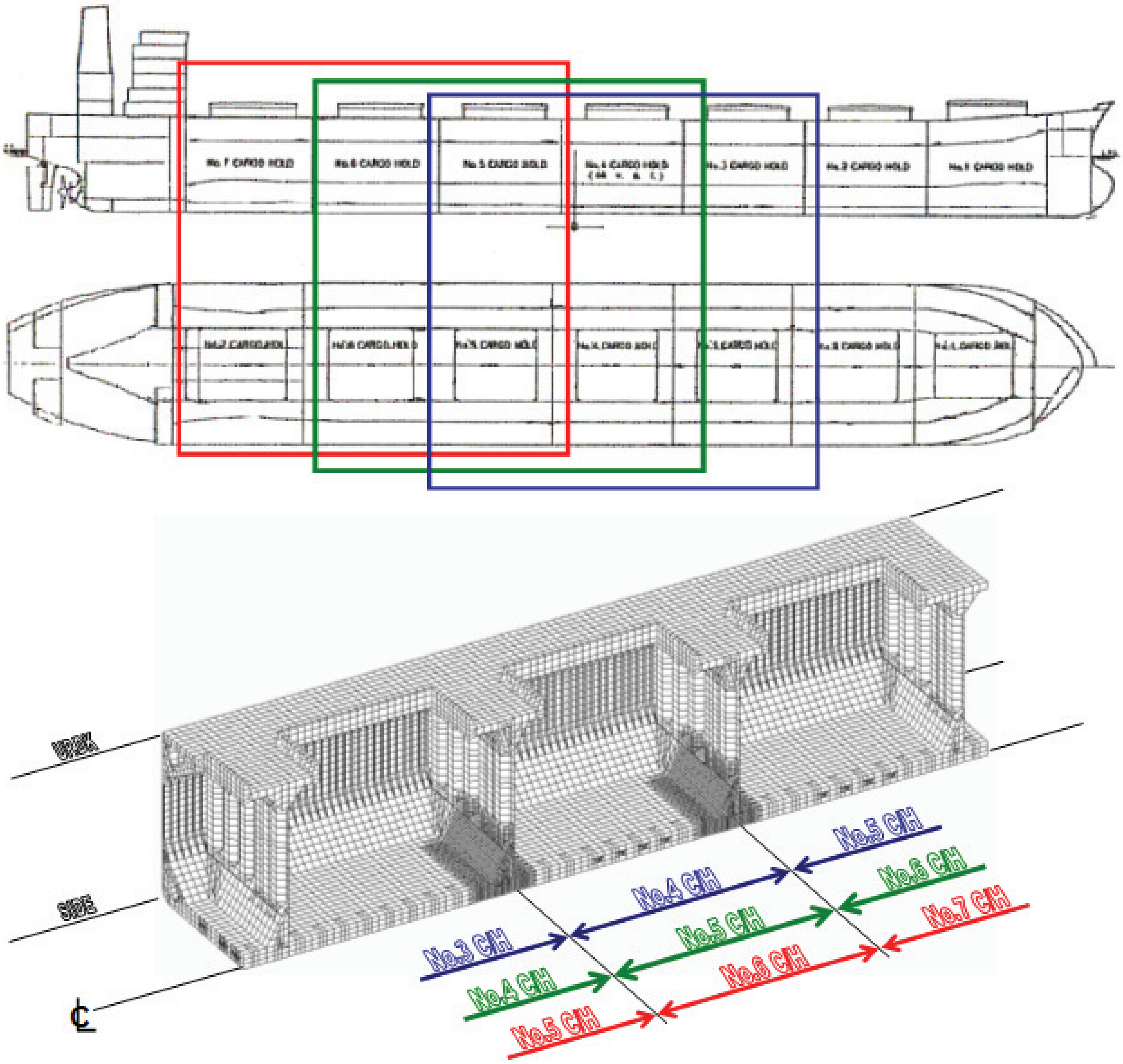

Figure 3: 3D - 3 Cargo Hold FE Models Extent

6. LOADING AND BOUNDARY CONDITIONS OF THE FE MODELS

There are ten (10) loading conditions to be considered as per ABS 2009 Rules Part 5C, Chapter 3, Section 3, Figure 1, which have been applied on each set of FE models of this study as applicable. (i.e. 1st set corresponds to cargo hold No 4 being the mid hold, 2nd set to cargo hold 5 being the mid hold and 3rd set to cargo hold No 6 being the mid hold). The hull girder shear force and bending moments as well as supports of the model at one end are applied as per the standard Safe Hull procedure.

Each model was analyzed for the applicable loading conditions by introducing its scantlings in the mid hold of a 3D 3-hold model. For cargo hold No 4 seven (7) loading conditions, for cargo hold No 5 five (5) loading conditions and for cargo hold No 6 six (6) loading conditions were applicable. Given the fifteen models used (5 double bottom heights per cargo hold), 90 cases in total were finally computed. CSR for bulk carriers boundary conditions (supports of the FE Model) are not yet finalized as per IACS CSR for bulk carriers, Re: (Technical Background for Rule Change (2009) Proposal 4-5 (Direct Strength Analysis) paragraph 1.2 comments to Ch. 7 Sec. 2 Table 2 (Ref. to IACS Knowledge Center (KC) 340)). This is the reason for which ABS SafeHull FEA procedures were applied, which consider the FE model fixed at one end and loaded at the other with hull girder shear force and bending moments.

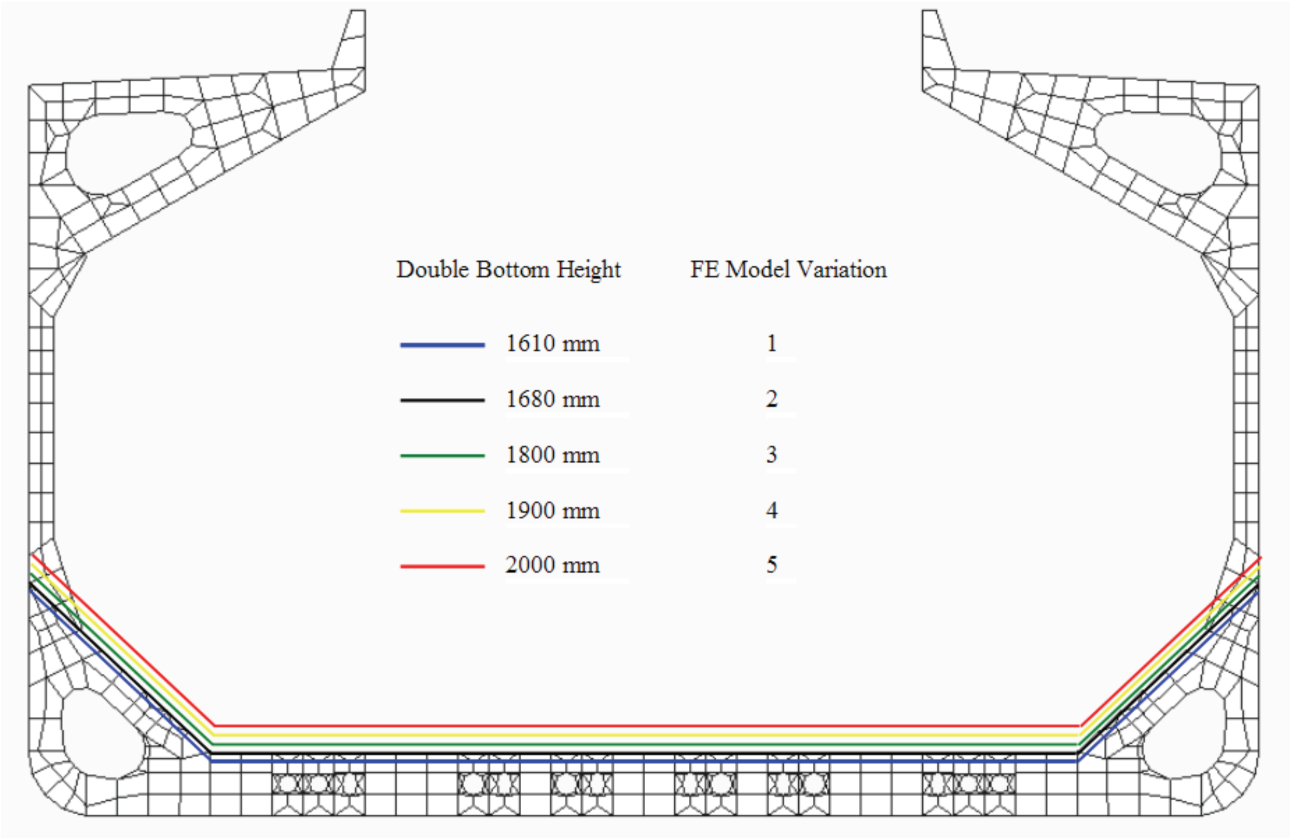

Figure 4: FE Model of the Midship Section for the Various Double Bottom Heights

7. SHEAR LOADING OF DOUBLE BOTTOM FLOORS AND LONGITUDINAL GIRDERS

The double bottom structure measures 22.7 m in breadth by 23.5 m in length, which forms an almost square grillage type structure with an aspect ratio of d_{DB}/B_{DB}=1.02, in each of the three holds analyzed. It consists of 8 transverse floors extending between the hopper tanks, equally spaced at 2580 mm and 5 longitudinal girders extending over the lower stools of the corrugated transverse bulkheads. These girders are spaced from the lower end of the hopper connection to the inner bottom at 4050 mm (Grd No 9), 4050 mm (Grd No 4) and 3250 mm (C.L. Grd) apart as show in Figure 2.(b). This compares well, in terms of the number of DB floors and girders, with MHI design shown in Figure 2 (a).

As shown in Table 2, the shear force distribution on the double bottom grillage members is uneven. The longitudinal girders are loaded heavier than the floors. This is due to the larger number of floors to girders (5 longitudinal girders as compared to 8 floors), although the double bottom grillage aspect ratio (d_{DB}/B_{DB}=1.02) is almost square. Evidently the 3 centrally located girders and 3 floors at the middle of the hold are the heavier load carrying members of the DB grillage. The 3 centrally located girders (center line and two adjacent girders) are carrying almost 150% of the load carried by the 3 mid-hold floors. However, A. Kawamura et al in their paper titled “Full scale measurements and strength analysis of 60,000 DWT bulk carrier – 1974” [14] (for a Panamax of 7 cargo holds bulk carrier – see Fig. 2a), have shown that at an aspect ratio of d_{DB}/B_{DB}=0.966 the 8 floors should take slightly more load than the 5 girders per hold. That means that the number of floors to girders of current designs of bulk carriers is not proportionally arranged for the anticipated DWT and maximum hull girder loading. In addition, the [15] paper entitled, “Structural strength of large bulk carriers” of Mitsubishi Heavy Industry, concludes that sufficient care should be paid for the balance of the strength of the adjacent structure. Furthermore, the deformations in the hold will also increase appreciably. In a companion paper to the present one we will show that if the aspect ratio of the DB grillage is increased to 1.02, this effect becomes appreciably larger (almost doubled).

The shear stresses on the double bottom girders for the basic ship, shown in Table 3, exceed the allowable limits, while the floors are stressed well below their allowable limits. Furthermore, the shear stresses decrease considerably as the DB height increases. This is due to the additional shear area available by the corresponding increased height of the girders and floors. Current shipyard practice to account for this overstressing is by fitting small thick inserts (commonly referred to as “postage stamp” type) at the upper end connection of the longitudinal girders to the inner bottom in way of the lower stool side plate, as shown in Figure 5. These inserts are commonly applied by the builders / designers to most of the latest designed Panamax and Handymax bulk carriers. However, the increased stiffness of the patch attracts more load thus affecting adversely the adjacent structures (floor, inner bottom, lower stool side and lower stool diaphragm plating). It therefore follows that in order to ensure satisfactory stress levels at the end connections without the need of the small thick plate inserts, the double bottom height needs to be increased.

The dominant loading conditions for the double bottom grillage to produce the maximum stress values presented in Table 3, is the oblique seas conditions. It is therefore unfortunate that CSR do not consider oblique seas yet, despite the insistence from the Greek shipping industry.

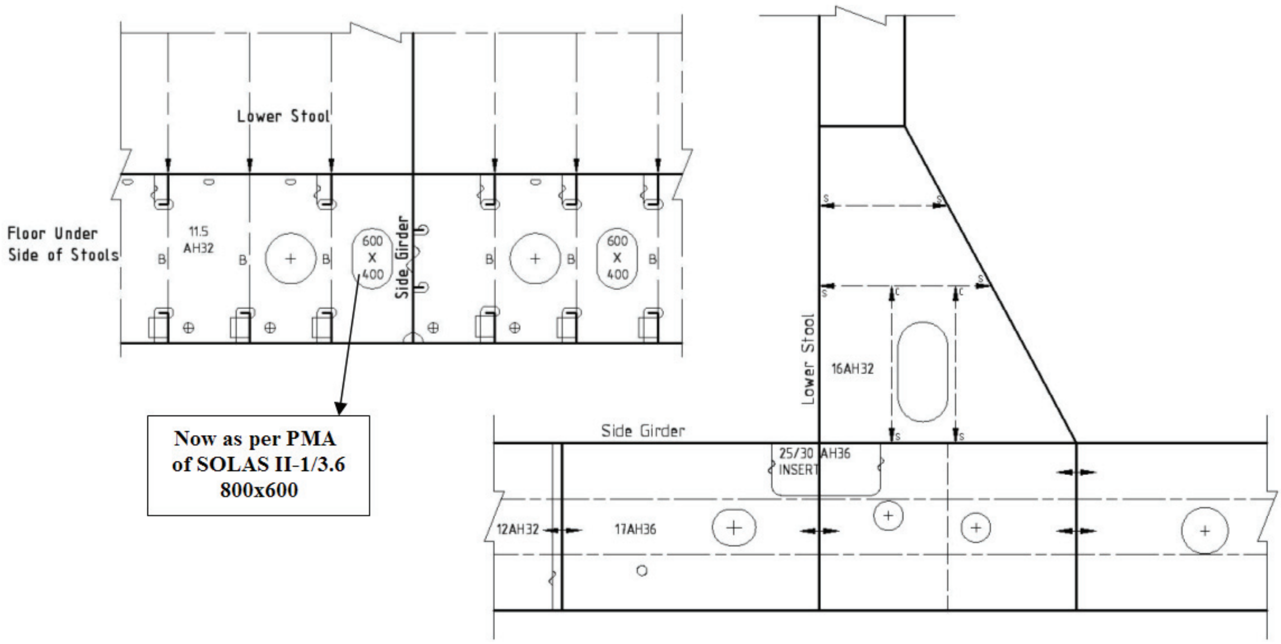

Figure 5: Typical Double Bottom Long. Girder and Floor connections in way of the Lower Stool - Showing quality of material & thickness of critical members [i.e. 25.0/30.0 AH36 girder “postage stamp” (insert) plate welded to 11.5 AH32 (floor)]

Table 2: Shear Load on Double Bottom Girders and Floors of Gargo Hold No4 for Loading Case 9 (Worst Case)

Shear Capacity of D.B Grillage for DB Height Variations						
DB Height (mm)	**S. Grd. No9 P (tons)**	**S. Grd. No4 P (tons)**	**C.L Grd. (tons)**	**S. Grd. No4 SB (tons)**	**S. Grd. No9 SB (tons)**	**Total shear Capacity (tons)**
1610	388.0	602.0	690.0	676.0	489.0	2,845.0
1680	397.3	607.3	694.0	683.3	497.8	2,879.7
1800	404.3	616.0	701.4	693.0	510.9	2,925.6
1900	412.4	621.4	709.2	700.6	521.7	2,965.3
2000	419.8	628.2	715.6	707.3	531.9	3,002.8

DB Height (mm)	**Fl. No 1 (tons)**	**Fl. No 2 (tons)**	**Fl. No 3 (tons)**	**Fl. No 4 (tons)**	**Fl. No 5 (tons)**	**Fl. No 6 (tons)**	**Fl. No 7 (tons)**	**Fl. No 8 (tons)**	**Total (tons)**
1610	217.0	313.4	384.5	434.0	441.7	392.1	323.4	211.0	2,717.1
1680	218.6	316.6	387.0	437.4	445.0	395.5	326.7	213.8	2,740.6
1800	222.6	322.6	387.9	443.0	451.2	402.0	332.0	218.5	2,779.8
1900	225.6	336.0	398.4	448.7	456.1	406.6	337.6	222.5	2,834.1
2000	228.8	332.6	403.0	453.5	461.0	411.4	342.6	215.2	2,847.3

Table 3: Ratio of Maximum / Allowable Shear Stress on Double Bottom Girders and Floors of Cargo Hold No4 LC 9 (Oblique Seas)

Shear Stress of D.B Grillage for DB Height Variations					
DB Height (mm)	**S. Grd. No9 P**	**S. Grd. No4 P**	**C.L Grd.**	**S. Grd. No4 SB**	**S. Grd. No9 SB**
1610	0.70	1.02	1.11	1.16	0.89
1680	0.69	0.99	1.09	1.14	0.87
1800	0.67	0.96	1.05	1.10	0.86
1900	0.66	0.92	1.02	1.07	0.84
2000	0.64	0.91	0.99	1.04	0.83

DB Height (mm)	**Fl. No 1**	**Fl. No 2**	**Fl. No 3**	**Fl. No 4**	**Fl. No 5**	**Fl. No 6**	**Fl. No 7**	**Fl. No 8**
1610	0.55	0.64	0.72	0.80	0.72	0.69	0.60	0.45
1680	0.54	0.62	0.70	0.78	0.70	0.67	0.58	0.43
1800	0.51	0.60	0.68	0.75	0.67	0.64	0.56	0.41
1900	0.49	0.58	0.66	0.72	0.67	0.62	0.54	0.39
2000	0.47	0.57	0.64	0.69	0.63	0.60	0.52	0.38

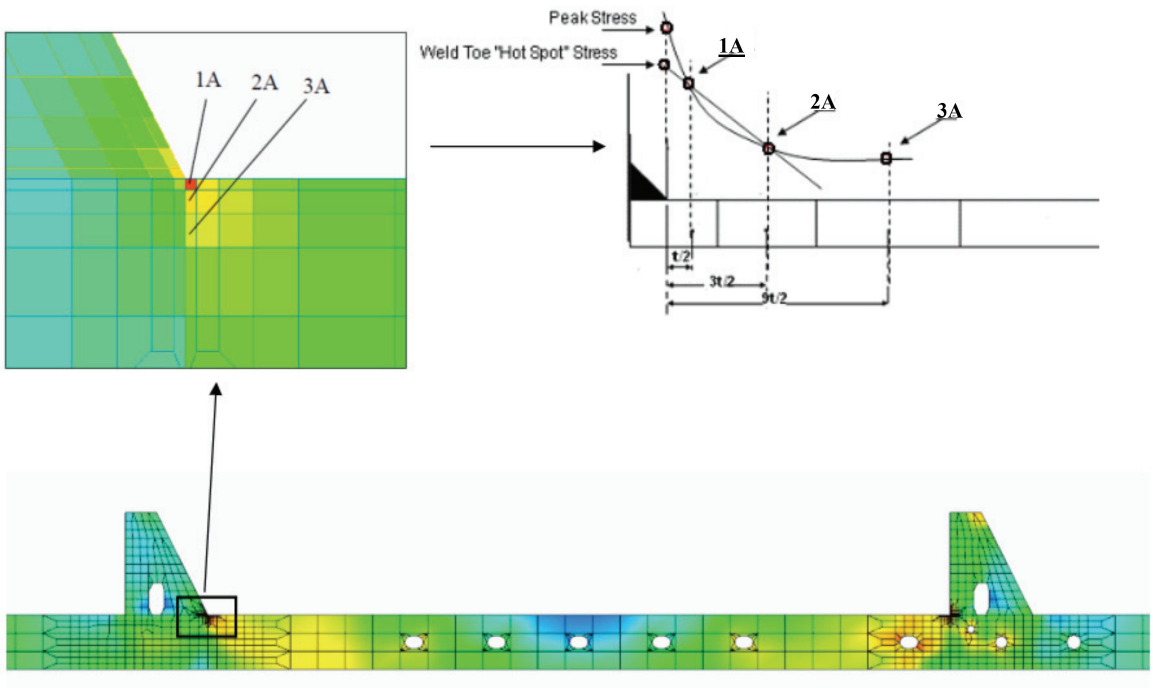

Figure 6: Hot Spot Stress Estimation Procedure

It was noticed that Panamaxes designed in 1974 with DWT 62,600 tons, have much heavier scantlings than the Panamax in this study (latest generation of bulk carriers) with DWT of 75,000 tons (almost 20% more DWT). See Figure 2 (a) compared to 2 (b) and also Table 1. A large number of bulk carriers of the late 90s and 2000s were designed with reduced double bottom height (i.e. from 1800 mm to 1680 mm) and a reduced number of their double bottom girders.

As shown in Table 3, the resultant stresses in floors and girders can decrease with the corresponding increase of the height of the double bottom to levels that are more reasonable, but yet not satisfactory. The problem with the reduced number of bottom girders will be the subject of a companion paper.

8. ASSESSMENT OF NOMINAL AND HOT SPOT STRESSES IN DOUBLE BOTTOM FLOOR AND LONGITUDINAL GIRDER

Resorting to solutions such as the "postage stamp" inserts as a local reinforcement is not strictly covered by the published IACS Class Societies past rules or the present CSR. The current linear FEA for thin shell analysis cannot handle adequately the behavior of such abnormal changes of thickness. The currently applied S-N curves for the calculation of fatigue are not designed / developed for such abnormalities without any correction. Designers have taken advantage of the increase of the mesh size of the FE elements, and by using solid floors and girders (without including in the FE model manhole and pipe openings – see DNV FE model in [16]), which disguise the resultant high stresses. Figure 8 below shows the resultant stresses on a double bottom girder modeled with and without the manhole and pipe openings. CSR for bulk carriers, Chapter 7, allows modeling the floors and double bottom girders without the openings. It is also shown that the critical areas as defined in SOLAS Ch. II-1 Reg. 3-6/4.2 may well be missed if the FE model does not depict accurately the manhole and pipe openings. In addition, for the new type of bulk carriers and oil tankers contracted for construction after 1st January 2005, SOLAS Ch.II-1/Reg. 3-6/5 requires the vertical manhole openings to be 800x600mm (from the customary 600x400mm). Evidently the same dimensions are to be maintained for clearance between obstructions (i.e. piping) and internals for the safe access of a person on a stretcher, a port state control inspector, crew member or class surveyor wearing a self-contained air-breathing apparatus. The omission (as per current version of CSR) of now enlarged openings from the FE model will exacerbate the resultant stress distribution around and adjacent to these openings located in critical areas (see Fig.5). This may force the designer to redesign partially the double bottom structure (by providing additional floors and/or girders), or as a whole (by increasing the double bottom height), to avoid the introduction of the very thick "postage stamp" (inserts) plating that will induce additional hot spot stresses due to increased stiffness locally. SOLAS Ch. II-1/Reg. 3-6/4.2 requires the establishment of the critical areas by calculation (and as per IACS UI SC 191/4.2 - by advance analysis techniques), applicable to the whole cargo block area (within 0.4L and outside 0.4L). CSR provide FEA procedures for the primary supporting members only of the cargo block area within 0.4L, and ignore the cargo block areas outside 0.4L.

The current S-N curves included in IACS CSR and ABS SafeHull 5-3-A1 Fig. 1 [1] were extracted from UK HSE Guidance Notes [8] for Offshore Structures (previously known as DEn) Section 21. In UK HSE Guidance Notes paragraph 21.2.12 c) states the following:

"For welded joints the fatigue performance is dependent on member thickness, performance decreasing with increasing thickness for the same stress range…..The basic design S-N curves are applicable to thickness less than the basic thickness t_B which for both classes P and T is 16 mm." The intent of this statement has not been considered in the IACS CSR.

Evidently the designers of bulk carriers in the late 90s and 2000s have taken advantage of the IACS Rules' omissions with regard to the variation of plate thickness and the method of calculating the hot spot stresses. This variation of thickness of heavily loaded plating creates a stress concentration in the immediate connections as well as in the transition zone between thick to thin plate.

In order to examine the structural behavior of the heavy insert, the mesh of the FE model in these areas was refined. The connections of the longitudinal girders, floors, lower stool diaphragms, lower stool side plating and inner bottom plating were modeled with fine mesh elements. The sizes of the elements next to the joints were equal to the thickness of the plate, the adjacent element 2 times the thickness of the plate, the next 3 times the plate thickness, and so forth as per ABS SH 5-3-A1/Figure 17 and [7]. Then the hot spot stress and stress concentration at the joint was calculated as shown in Figure 6. Hot spot stresses have been calculated as shown on Table 4.

The stress concentration factor is the hot spot stress divided by the nominal stress which, in this case, is about 2.0. The nominal stress has been calculated over $3t$ and corresponds to about 1/10 of the spacing of the longitudinal stiffeners. The allowable stress is as per ABS SH-DLA. It therefore follows that in order to satisfy the VM stresses criterion shown above, the height of the double bottom should have been raised well over the as per "basic ship" 1680 mm. The stresses shown above are well beyond the yielding and ultimate strength of the material. That means that a plastic hinge will form on the joints under consideration, and redistribution of the load will take place. Additional stresses due to lateral load and deflection have not been taken into account either in CSR's ultimate strength check [13] as demonstrated in [6] or in this linear FE analysis. Certainly the welds are stressed well over their capacity and cracks will form first on coatings [10] and then on the welds, and eventually propagate along the weakest path of the plate materials involved. This effect may well appear within the first few years of the vessel's life as described in [12].

In order to satisfy the allowable stress of the applicable rule, a further reduction of the nominal stress is required. This can be achieved with the increase of the double bottom height, the drastic increase of the thickness of floors and girders, the introduction of additional floors and girders, or a combination of all these. Obviously the most drastic solution would be the addition of girders / floors, since this would reduce the load carried by each member. The stresses calculated are at about 22% higher than the allowable. In this paper we investigated the effect that the increase of the double bottom height would have on the reduction of the stresses, as shown in Table 4. The companion paper to be issued shortly, investigates the optimum combination of the three alternatives in order to determine the most efficient solution.

Table 4 Ratio of Maximum / Allowable Stress Intensity at Double Bottom Girders

Double Bottom Girders Max. Nominal Stresses intensity with various Double Bottom Heights at LC 9 Cargo Hold No 4		
D.B. Height	**C.L Side DB Girder**	**No4 DB Girder**
1610	1.21	1.25
1680	1.18	1.22
1800	1.14	1.18
1900	1.11	1.15
2000	1.08	1.12

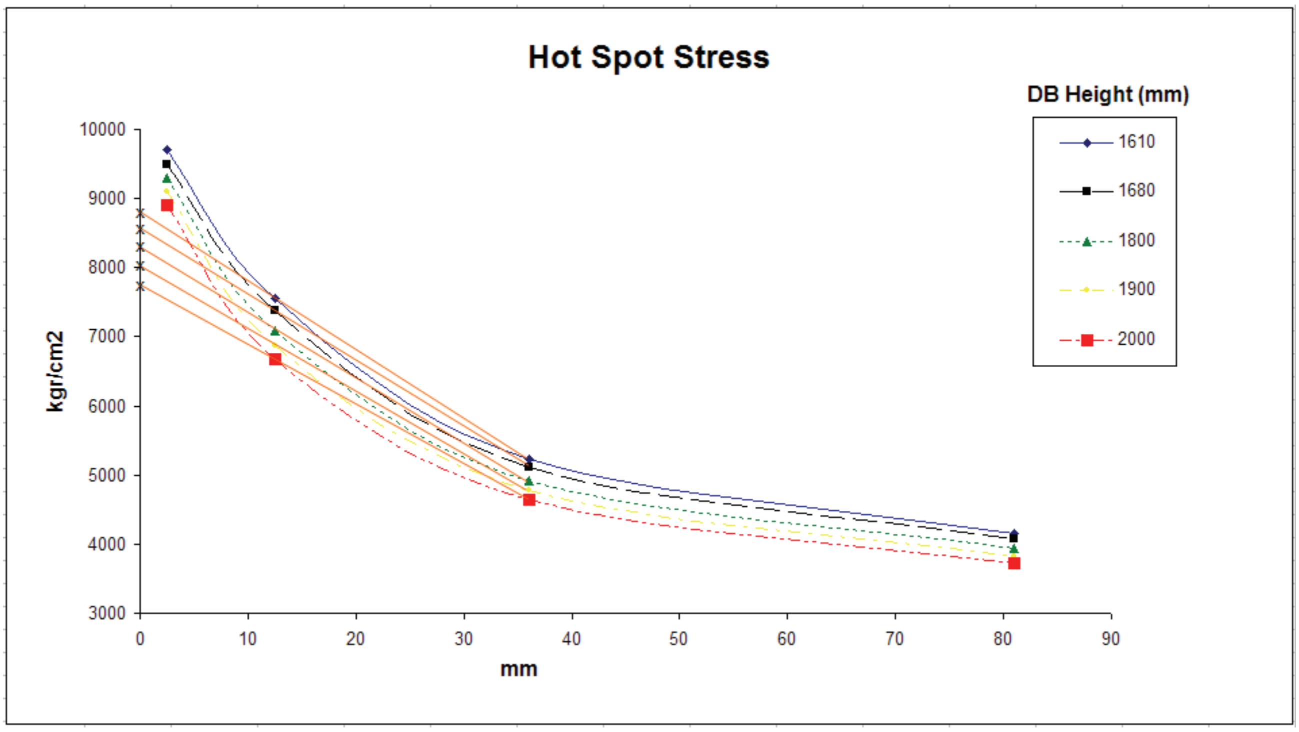

Figure 7 Hot Spot Stress Calculation [as defined in Fig. 6]

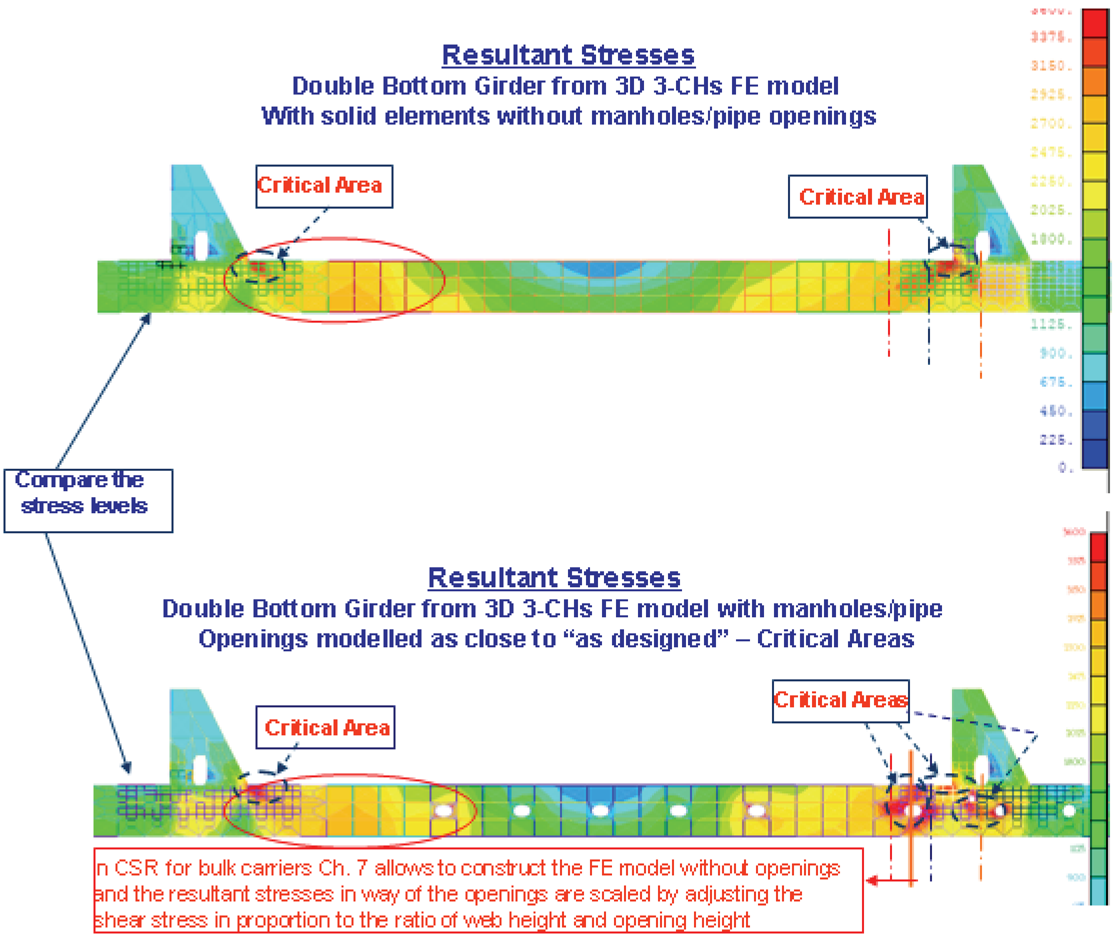

Figure 8: Resultant stresses in the same double bottom girder modeled with and without manholes – Redistribution of stresses around the manholes show the multiplicity of critical areas as defined/required by SOLAS Ch. II-1/Reg 3-6.4.2 versus the FE model without the manholes

9. CONCLUSIONS

In conclusion, if the stress reduction is to be obtained solely by increasing the double bottom height of the vessel investigated, this height should be drastically increased to well above 2000 mm instead of the basic ship's value of 1680 mm. This height could be reduced to about 1900 mm if additional double bottom girders are introduced, as will be shown in the companion paper. This coincides with the views of other investigators such as A. Kawamura, D Sakai et al., 1974 paper entitled " Full scale measurements and strength analysis of 60,000 DWT bulk carriers" [14].

The current IACS CSR formulation (d_{DB} = *B/20 or 2 m* which ever is less) requires urgent revision. The formula that controls the double bottom height should include parameters related to the draught of the vessel, the aspect ratio of the double bottom (i.e. width of the double bottom between the hopper tanks, over the length of the cargo hold, in relation to the vessel length). In addition more realistic spacing of the double bottom floors and girders should be adopted to ensure double bottom support and accurate transmission of more balanced shear forces to the transverse bulkheads. The IACS CSR requirement concerning the calculation of the minimum double bottom height should not include vague statements like "..in general.." or "… both DB girders and floors greater spacing maybe accepted depending on the FEA results" for the reasons highlighted in paragraph 3 of this paper.

The omission of the manhole and pipe openings from the FE model may well contribute to structural failures that may require redesigning in part or in whole, of the double bottom structure (say by adding floors/girders, or increasing the height of the double bottom). This may contribute to the failure of establishing the position of all the critical areas within the cargo block area as required by SOLAS Ch. II-1/Reg 3-6/4.2.

Table 5 below provides a comparison between the current and old rule formulations, as well as values for a proposed interim formula for establishing a minimum acceptable double bottom height, (based on the proposed spacing of the double bottom floors and girders), which will be further refined in the companion paper, already mentioned.

Table 5 Double Bottom Height – Spacing of floors and girders of the "as designed" bulk carrier compared to the values produced by the FEA, "IACS CSR" and "Proposed Formulation".

Items considered	Values of "As Designed" (mm)	Values as calculated by FE (mm)	IACS CSR	IACS CSR Requirements (mm)	Proposed Formulations	Proposed Formulation (mm)
DB Height	1680	>>1900	whichever is lesser B/20 or 2 m	1610	$d_{DB} = 45B_{DB}+80\sqrt{d} + (L+240)$	**1772**
Spacing of DB Floors	2580 (Frame Sp. 860)	2580	whichever is lesser 3.5 m or 4 frames spacing	3240	whichever is lesser 3.0 m or 3 frames spacing	2580
Spacing of DB Girders	4050 (Sp.of longs 810)	3240	whichever is lesser 4.6 m or 5 spacing of longs	4050	whichever is lesser 3.0 m or 4 spacing of longs	3000

10. ACKNOWLEDGEMENTS

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