Effects of hull deformations on ship displacement

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ABSTRACT: The paper presents first an alternative draft survey procedure for assessment of displacement of longitudinally deformed ship hull. Next, the paper considers all potential positions of outer shell local deformations under static loads on the immersed ship hull. The theories of isotropic and orthotropic plate bending are applied in order to assess local deformations. Consequently, the total change in the locally deformed underwater hull volume is assessed by employing numerical integration over the entire immersed hull. The procedure is illustrated on a bulk-carrier recently built in Croatia. The results are presented graphically in order to provide insight to all major hull volume changes due to local deformations for different load cases in ship's service, pertinent to specific compartments, substructures and levels of deformation. Finally, some general suggestions for ship's displacement corrections due to local deformations are given.

1 INTRODUCTION

The ship's displacement plays important role in the validation of ship's operational efficiency. Nevertheless, the determination of displacement is not always accurate with respect to the environmental conditions and conditions of the ship's hull. Numerous related conditions on-board are practically imperceptible and immeasurable. Some uncertainties come from draft readings, different global, local, thermal, longitudinal or transverse, as well as permanent or temporary deformations of an immersed ship hull. Additionally, a hull is subjected to fouling, corrosion, damages, reparations and aging. Moreover, the conditions of survey sometimes do not provide precise observations due to waves, ship motions or heavy access to draft marks on board. Normally in the end, accurate hull local and global deformations cannot even be considered in practical determination of the displacement on-board during draft and deadweight surveys in the ship's service, particularly in rough weather conditions. Hence, it is nearly impossible to determine the ship's accurate displacement, and any method that simplifies the procedure or improves the accuracy should be highly appreciated.

2 GLOBAL HULL DEFORMATIONS

In traditional practice of a draft survey, the drafts are observed on draft marks or measured by devices placed aft, forward and on ship's portside and starboard close to amidships. The means of drafts are recalculated to positions in virtual coincidence with respective perpendiculars and midship section, usually designated as observed drafts aft, amidships and forward, as T_A, T_M, T_F., Figure 1. A commonly adopted method of marine surveys for assessment of the effects of small global hull longitudinal deflection on the ship displacement is to perform standard hydrostatic calculations supposing parabolic deflection shape with an equivalent value of draft amidships, denoted as "quarter mean draft" defined as:

$$T_M^{w1/4} = \frac{T_A + 6 \cdot T_M + T_F}{8} \qquad (1)$$

A more general case denoted as the *CroMark®* standard draft T_{CM}, is when instead of a constant 1/4, a variable draft correction factor C_d is introduced:

$$T_{CM} = \frac{T_A + T_M\,(2/C_d - 2) + T_F}{2/C_d} \qquad (2)$$

The dimensionless draft correction factor C_d due to deflection can be derived by only basic waterplane characteristics, such as the moment to change trim one unit *MT1*, tons per unit of immersion *TP1*, water plane coefficient C_{wp}, longitudinal water plane moment of inertia I_L and water plane area A_{wl}. The correction factor can be easily calculated from available ship's hydrostatic particulars Ziha (2001), as shown:

$$C_d = \frac{I_L / A_{wl}}{(L_{wl}/2)^2} = \frac{MT1}{TP1} \cdot \frac{L_{pp}}{(L_{wl}/2)^2} \approx \frac{1}{3(3 - 2C_{WP})} \qquad (3)$$

The more accurate draft correction factor allows an alternative placement of draft marks, Ziha (2001). The positions alongside the ship's hull, centered with respect to longitudinal centre of flotation *LCF*, where the observed drafts are equal to the equivalent draft Ziha (2002), Figure 1, amounts to:

$$x_d = \pm L_{wl}\sqrt{C_d}\,/\,2 \qquad (4)$$

Following the sensible assumption that the position of the maximal deflection is closer to the center of flotation *LCF* than to the deflection amidships, the equivalent draft is defined by only two *CroMark®* draft readings aft CM_A and forward CM_F, Figure 1.

The *CroMark®* standard equivalent draft *CM* yields to more accurate displacement assessment of a deflected hull employing the standard hydrostatic data.

The usually applied "quarter mean draft" or "mean of mean draft" correction for hull hogging or sagging is not appropriate for modern large merchant ships with relatively high waterplane coefficients. Therefore, the *CroMark®* procedure offers an alternative, quick, practical and more accurate rational method based on the standard and permanent hydrostatic particulars for assessments of drafts and displacement of a sensibly deflected and trimmed ship hull during a draft and deadweight survey.

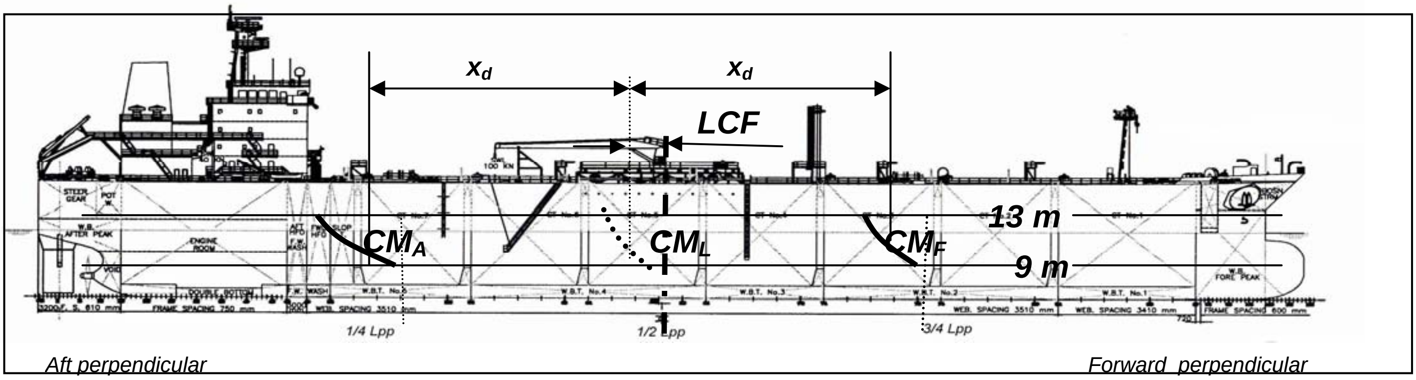

Figure1. The CroMark draft marks position alongside ship hull of m/t "Stinice"

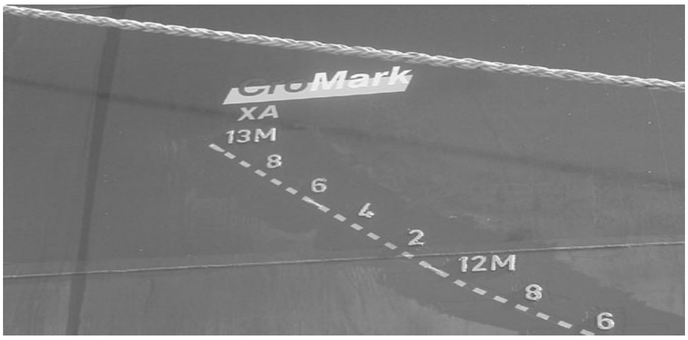

Figure 2. The CroMark draft marks aft on m/t «Stinice»

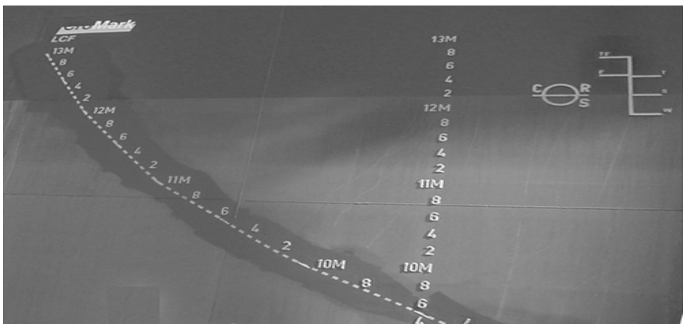

Figure 3. The CroMark draft marks midships on m/t «Stinice»

Since the observed *CroMark®* drafts aft and forward are centered with respect to the *LCF* at positions x_d, the *CroMark®* standard equivalent draft *CM* for displacement calculations accounts for the hull longitudinal deflection and virtually coincides with respective center of flotation, Figure 1:

$$CM = \frac{CM_A + CM_F}{2} \qquad (5)$$

The applied *CroMark®* draft correction factor based on the true waterplane shape differs significantly from the traditionally applied constant correction factor of 1/4 for most of the modern merchant ships. Moreover, the *CroMark®* correction factors can be easily calculated on the basis of hydrostatic particulars and attached to the ship's instruction book for routine application during marine surveys.
The simplest application of the *CroMark®* improved draft correction factors on traditional draft readings aft, amidships and forward yields the more accurate displacement of a deflected ship during a deadweight survey. However, both the "quarter mean draft" and the *CroMark®* procedures can be applied only for reasonable ship's trim and hull deflection.
Many merchant ships cannot have draft marks on perpendiculars and amidships due to the hull form and additional recalculations due to draft marks position are needed anyhow. Since the traditional placement of draft marks was instituted when the ships were of different hull form and not as long as modern merchant vessels, the alternative draft marks placed closer to the amidships, usually in the area of the parallel hull sides, Figure 2, 3, may lead to more accurate and less troublesome draft readings on large ships due to less intense motions and due to easier, near simultaneous view by observers on board or ashore, eliminating the need for using a boat for inspection of draft marks.
It appears feasible to assess a deflected ship's displacement with improved accuracy by placing draft

marks and/or automatic measurement devices nearby the load line only in two positions alongside a ship hull, preferably portside and starboard, which provide identical equivalent and observed drafts. Since the standard equivalent draft resulting from the averaging of draft readings at alternative placement of draft marks virtually coincides with respective ship's center of flotation, the *CroMark®* survey procedure yields to improved displacement assessment of a sensibly deflected hull, and moreover, in the same time, it accounts for the correction due to the reasonable ship's trim Ziha (2002). The third draft reading is to be introduced only when the amount of hull deflection is of a particular interest, what is seldom required in ship service. In the cases when the ship's trim or the deflection of the hull are too large, the additional *CroMark®* draft readings in combination with the traditional draft marks at perpendiculars and amidships improve the accuracy of the lengthwise integration over inclined and deflected sections using Bonjean's curves. The alternative placement of draft marks in positions of greater hull breadth in the area of the parallel mid-body facilitate the fitting of draft marks and adds sense for averaging both portside and starboard draft marks, even for ships with significant heeling angle. The loaded conditions with sensible trim and small deflections are of utmost interest for deadweight survey, much more than the ballast conditions, and therefore the placement of *CroMark®* draft marks nearby the load line, in combination with draft marks at stern which impacts on propeller immersion and rudder effectiveness and at bow, which affects maneuverability and slamming, appears practical for surveyors due to easier inspection and to ship-owners and crew due to accuracy.

The purpose of the next consideration is to estimate the upper limits of the effects of local deformations on changes of ship's displacement using appropriate procedures based on ship's theory, and to present results on an example ship built in Croatia.

3 LOCAL DEFORMATIONS

The ship's hull is also subjected to local deformations affecting the hull volume. Local deformations can be abstracted on several levels of substructures, e.g. hull section Figure 4, or a bottom Figure 6.

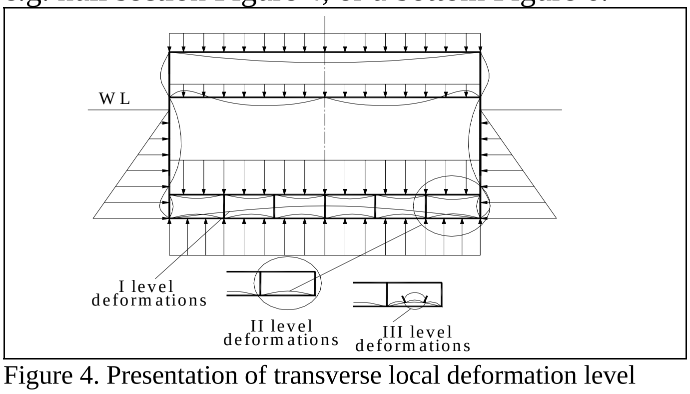

Figure 4. Presentation of transverse local deformation level

Since the ship's displacement in service is in general determined on a still water, only the local deformations under static loads on the immersed shell are relevant for assessment of hull volume changes. Permanent plastic deformations on old ships outer shell might be included as initial losses of displacement.

Following the reasonable engineering assumptions generally used in semi-empirical approach to ship construction about mutually supporting role of dominant hull substructures and girders, such as longitudinal and transversal bulkheads with respect to bottom, sides and decks, or sides with respect to bottom and decks, or bottom with respect to bulkheads and sides, or decks with respect to bulkheads and sides, etc., the relevant local deformations of the hull stiffened panels are considered in three levels, e.g. hull section Figure 4 and bottom panel Figure 6, as follows:

- *I level* (primary) deformations: panels between dominant substructure (e.g. bottom panel between two longitudinal and transversal bulkheads, or side panels between bottom, deck and bulkheads)
- *II level* (secondary) deformations: stiffened panels between dominant girders (e.g. bottom and side panels between longitudinal and transversal girders of large substructures)
- *III level* (tertiary) deformations of plates between two stiffeners or stiffener and girder (e.g. bottom plating between longitudinals and side plating between frames)

3.1 *Assessments of local deformations*

Numerical and analytical methods are considered.

The finite element method (FEM) for this application requires a very fine 3-D FEM model of the entire ship structure, or at least, a set of very fine 2-D FEM models pertinent to all principal panels of the hull structure, Figure 5. Such an approach is feasible but time consuming, particularly if the FEM model is not available from the construction phase.

Therefore, for this application, analytical methods based on the plate bending theory are preferred. The isotropic plate method is found appropriate for hull plating between stiffeners and/or girders which contribute to the third level of local deformations.

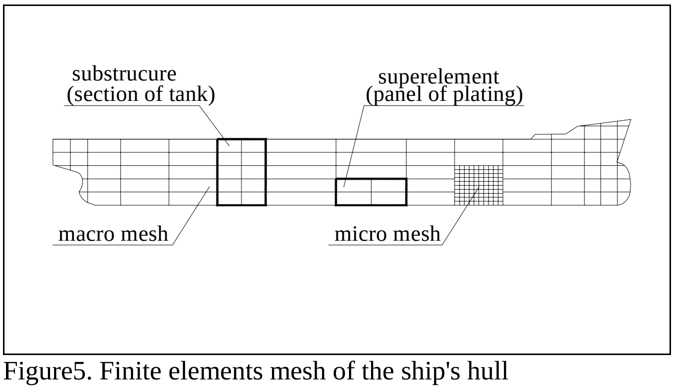

Figure5. Finite elements mesh of the ship's hull

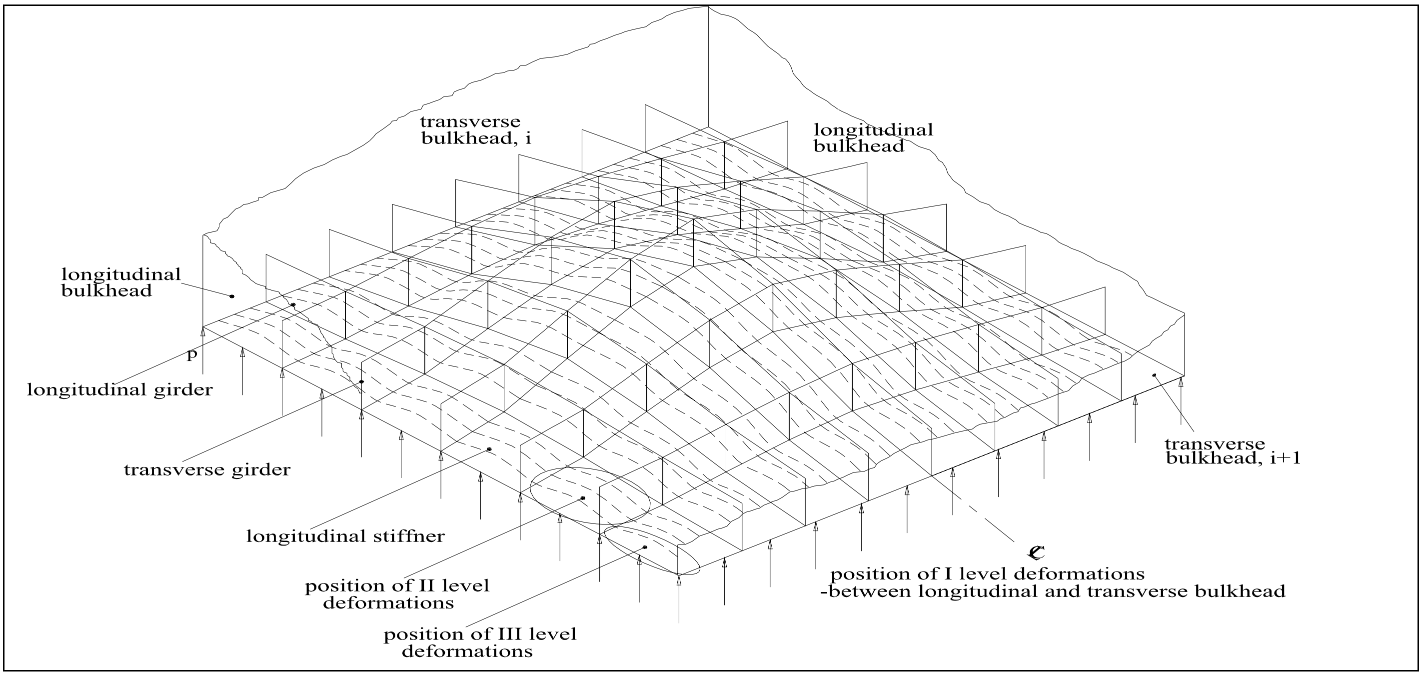

Figure 6. Local deformation levels of ship's bottom

The procedure benefits of plate bending equation solutions presented by diagrams. The deflection in the middle of the plate banded under lateral pressure p according to Schade's diagrams in Hughes (1988), using factor K (depending on η i ρ) is as follows:

$$w_m = K\frac{pb^4}{Ei_b} \tag{6}$$

where η = torsion coefficient; ρ = virtual plate aspect ratio; and i_b = unit moment of inertia of girder parallel with the plate shorter side. The paper actually made use of more sophisticated diagrams accounting also for torsional stiffness given by Marguerre and Woernie in Hughes (1988), which define the deflection amidst the plate under bending as:

$$w_m = \frac{5}{384}\frac{p\cdot(ab)^2}{\sqrt{D_x D_y}}\cdot A \tag{7}$$

where $D_{x(y)} = \dfrac{Ei_{x(y)}}{1-\mu^2}$ =bending stiffness in directions x(y); and A=factor that depends on η and ξ=1/ρ.

The plate bending calculations for the purposes of this paper were carried out by two computer programs, one using digitized curves from diagrams and another by using Fourier-series expansion.

3.2 *The procedure of calculation*

Calculations of changes of hull volumes were performed in five steps, as presented in the sequel:

1. For every immersed substructure of length a and width b between two adjacent transverse bulkheads under local pressures, the displacement at crossings of principal girders are calculated, supposing orthotropic plate fully rigidly clamped at edges. Each volume $V^1_{(n)m}$ of the *I* level deformations is calculated by numerical integration, where $V^1_{(n)m}$ = volume of m-*th* substructure of n-*th* compartment.
2. For every stiffened panel between adjacent transvers and longitudinal girder of length a and width b under local pressures, the displacements in the middle of the panel are calculated, supposing orthotropic plate fully rigidly clamped at edges. Each volume $V^2_{(n)k,m}$ of the *II* level is calculated by numerical integration, for *k-th* panel of *m-th* substrucuture.
3. All volumes $V^2_{(n)k,m}$ are summarized:

$$V^2_{(n)ukm} = \sum_{k=1}^{k=no.panel.} V^2_{(n)k,m} \tag{8}$$

where $V^2_{(n)ukm}$ = total volume of the *II* level deformations of *n-th* compartment of *m-th* substructure.
4. The deflection curve of the flat plating between stiffeners of length a and width b, rigidly clamped at edges is taken in a trigonometric form as the first term in a series of Navier's solutions:

$$w(x,y) = \frac{w_m}{4}\cdot(1-\cos\frac{2\pi x}{a})(1-\cos\frac{2\pi y}{b}) \tag{9}$$

The maximum deflection w_m in the middle of the plate is obtained under assumption of an isotropic plate using appropriate diagram data. The overall volume $V^3_{(n)j,m}$ of *III* level for *j-th* part of flat plating between stiffeners is defined by integration as:

$$V^3_{(n)j,m} = \int_0^a\int_0^b w(x,y)\cdot dx\cdot dy = w_m\frac{ab}{4} \tag{10}$$

5. All volumes $V^3_{(n)j,m}$ are accumulated:

$$V^3_{(n)ukm} = \sum_{j=1}^{j=no.of smooth.pl.fields} V^3_{(n)j,m} \tag{11}$$

where $V^3_{(n)ukm}$ = total volume of *III* level deformations of *n-th* compartment of *m-th* substructure.

Steps from 1 to 5 were carried out for each part of the test ship for all three levels of deformations, and the results are presented in the sequel.

3.3 *Example of calculation*

The effect of local deformations on ship’s displacement is illustrated on the bulk-carrier “Don Frane Bulic” (Yard no. 399 Shipyard “BRODOSPLIT”, Split, Croatia) with five cargo holds and engine room placed aft. The main particulars are as follows:

$L_{oa}=187.63\ m$ length overall
$L_{pp}=179.37\ m$ length between perpendiculars
$B=30.80\ m$ width, D =15.45 *m* depth
$d_D=10.10\ /\ 10.80\ m$ design draft / maximum draft
$\Delta=50112\ /\ 46549\ t$ corresponding displacements
$DWT=41600\ /\ 38100\ t$ corresponding deadweights.

The ship was normally longitudinally stiffened, except the transversely framed sides, Figure 7.

Complete calculations for all three levels of deformations of bottom and sides were carried out only for the cargo hold compartments. While in case of engine room and fore and aft peaks, the first two levels of deformations were unattainable due to high rigidity of these parts of the hull, and only the *III* level deformations are accounted for.

Calculations were carried out for drafts where the structure significantly changes its character Figure 7. Draft $d_1 = 5.98\ m$ correspond to the top of the longitudinally stiffened hopper tank, and bottom of the transversely framed sides. Draft $d_2 = 11.15\ m$ corresponds to the top of the sides and bottom of the longitudinally stiffened wing tanks. Examples of how sub-structuring is carried out and the deformation level considerations are given in Figures 8, 9, 10.

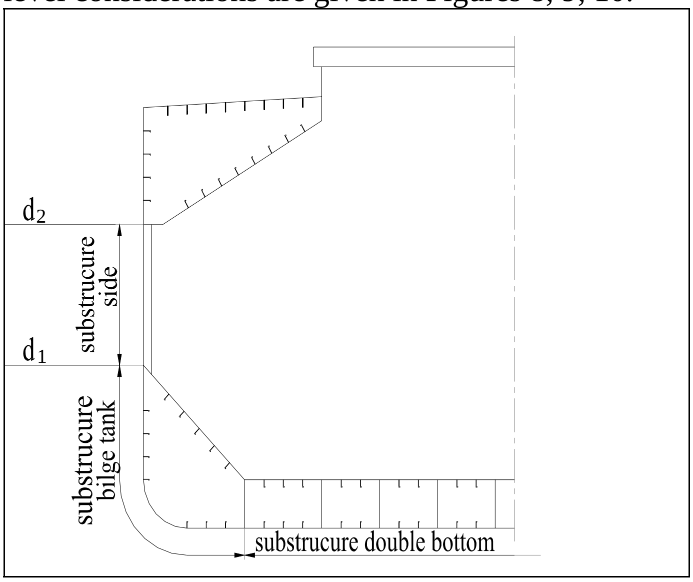

Figure 7. Bulk-carrier hull substructures

Calculations according to procedural steps 1 to 5 gave the following results:

-for $d_1= 5.98\ m$ loss of displacement is $V= 7.82\ m^3$
-for $d_2=11.15\ m$ loss of displacement is $V=17.59\ m^3$

Results by levels of deformations for cargo Hold no. 1 are presented in Figure 11. The results for the whole ship indicating the contribution of each compartment are given in Figure 12, in order to estimate the contribution of each compartment and each deformation level, wherever that may be of interest.

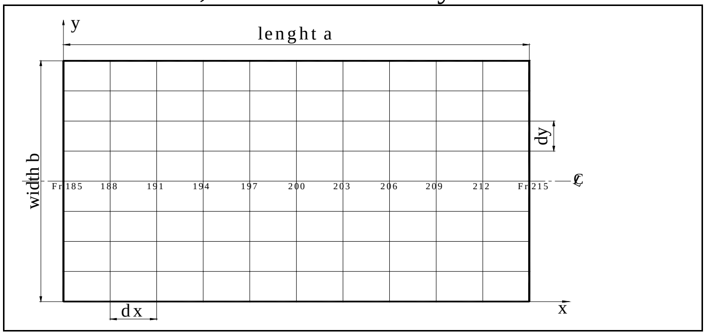

Figure 8. Double bottom, Hold no. 1, I level deformations

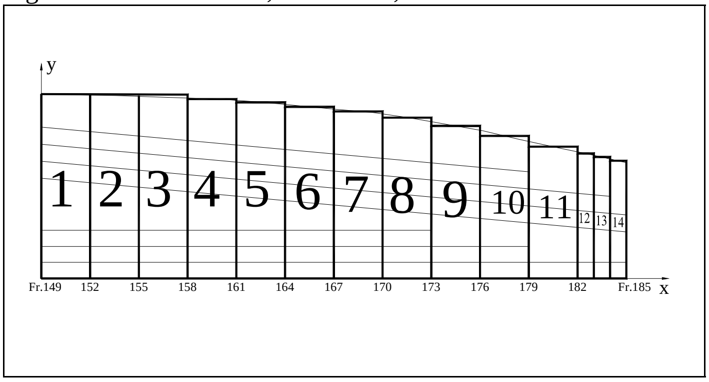

Figure 9. Wing tank, Hold no. 2, II level deformations

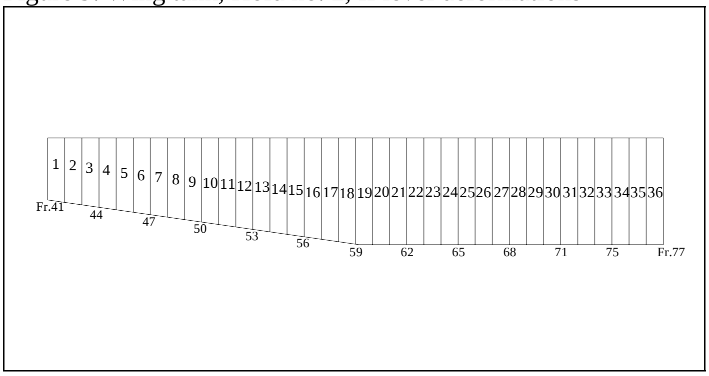

Figure 10. Side, Hold no. 5, III level deformations

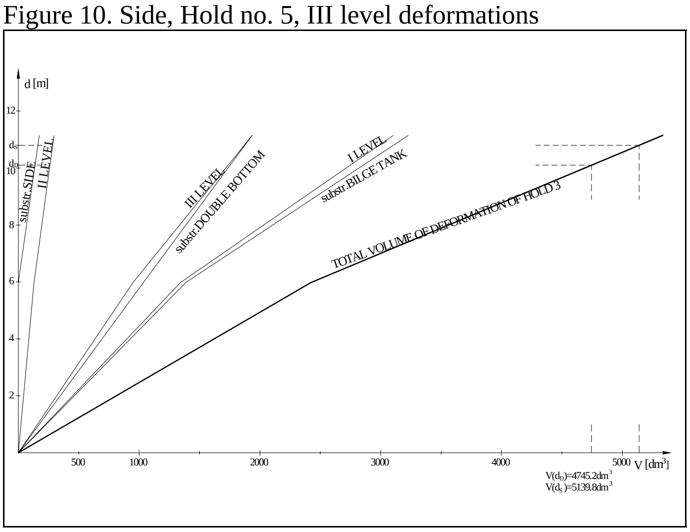

Figure 11. The volumes of local deformations at Hold no. 3

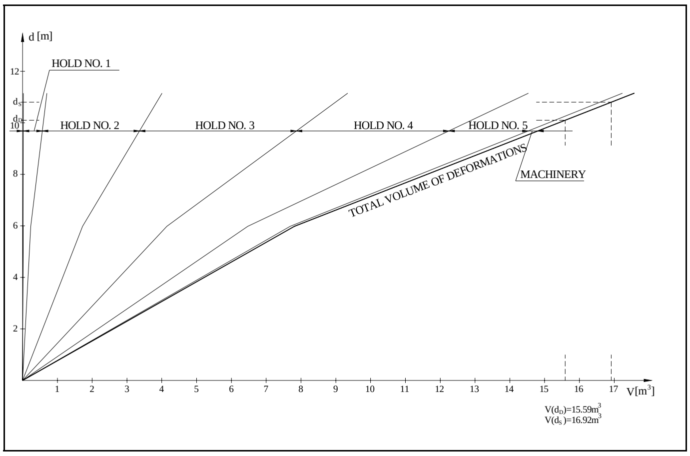

Figure 12. The total volume of local deformations for all holds

3.4 *Correction of displacement*

Normally in practice of marine surveys the theoretical displacement is corrected by using of a coefficient of appendages as shown:

$$\Delta = \nabla \rho_{sea} C_{ap} \tag{12}$$

where ∇ = volume of displacement on measured draft d; and ρ_{sea} = density of the seawater.
The coefficient of appendages C_{ap} accounts for thickness of ship's plating, volumes of bilge keel, screw, rudder, rudder horn or posts, struts, bossings and other appendages. Normally the coefficient of appendages C_{ap} depends on draft of ship, but in practice of displacement survey a constant coefficient of appendages C_{ap} is usually assumed. In order to simplify the displacement survey the effect of appendages is included in a joint displacement correction factor implying the water density amounting to $\rho_{sea}\, C_{ap}=1031\ kg/m3$.
In the sequel, the amount of the coefficient of appendages C_{ap} will be reconstructed by using the results of the formerly presented calculations.
The hull volume on draft $d_s = 10.10\ m$ derived from appropriate hydrostatic data amounts to $\nabla = 45186.3\ m^3$. The calculated volume accounting for appendages amounts to $\nabla_{ap} = 45329\ m^3$. Consequently, the volume of appendages amounts to $\nabla_{ap} - \nabla = 142.7\ m^3$
Therefore, the coefficient of appendages C_{ap} is obtained as follows:

$$C_{ap} = \frac{\nabla_{ap}}{\nabla} = \frac{45329}{45186} = 1.0031$$

The total loss of volume due to all three levels of local deformations on draft d_s is calculated earlier and amounts to $V_{def} = 15.6\ m^3$. Consequently, the volumes are decreased to amounts $\nabla' = 45170\ m^3$ and $\nabla'_{ap} = 45313\ m^3$. Finally, the coefficient of local deformations C_{ld} in that case can be calculated as:

$$C_{ld} = \frac{\nabla'_{ap}}{\nabla_{ap}} = \frac{45313}{45329} = 0.9997$$

At the end, the total displacement with appendages and with effect of local deformations is obtained as:

$$\Delta = \nabla \rho_{sea} \frac{\nabla_{ap}}{\nabla} \frac{\nabla'_{ap}}{\nabla_{ap}} = \nabla \rho_{sea} C_{ap} C_{ld} = \nabla \rho_{sea} C'_{ap} \tag{13}$$

The concluding remark in this consideration is that the coefficient of appendages C'_{ap} can be corrected for local deformations C_{ld} as follows:

$$C'_{ap} = C_{ap}\, C_{ld} = C'_{ap} = 1.0031 \times 0.9997 = 1.0028$$

3.5 *Remarks on results*

Calculations in the paper were performed in case of a bulk-carrier built in Shipyard "Brodosplit", with 5 cargo holds, 15 main substructures of bottom and side (*I level*), 14 transverse framed panels and 64 longitudinal stiffened panels (*II level*) and 1280 flat plates between stiffeners and girders (*III level*).
The total ship's displacement is in the presented example expectedly reduced relatively by a very small amount of *0.034%* as a result of local deformation. However, the diminution of volume with respect to all appendages due to volume losses of local deformations in this example is relatively high, amounting to about *11%* of the volume of appendages.

4 CONCLUSION

The *CroMark®* draft marks were at first fitted on m/t "Stinice" with permission of American Bureau of Shipping. The captain's reports about the practical usage of the *CroMark®* procedure on board are encouraging.
The procedure for estimation of the effect of local deformations of immersed shell on the displaced volume of ship's hull, based on theory of isotropic and orthotropic plate bending was not intended to be a routine one. The primary aim was to provide some experience in assessment of the order of magnitude of these effects. Therefore, the application of more sophisticated but time consuming FEM procedures for the problem elaborated in this paper does not appear rational. In conclusion of these considerations, the usually applied coefficient of appendages in service conditions might be slightly reduced in order to account for the local deformations of the ship's outer immersed shell.

LITERATURE

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