Evaluation of Strength for Double Hull Structure in Initial Hull Planning and Optimization of Hull Weight with Genetic Algorithms

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Summary

This is a proposal for the adoption of a simplified means for structural strength calculation based on energy method. Adopting this approach, we may, during initial planning stages, evaluate the strength characteristics of double hull structures by using Lagrange's Multiplier Method to guarantee the continuity of deflection angles with adjoining structures.

The calculation is accomplished by multiplying the nondimensional element stiffness matrix that remains constant for various combinations of structural dimensions by the stiffness ratio. This method makes data inputs and calculation of the stiffness matrix simpler and more expeditious.

The results of calculations using this method have been compared with theoretical values and numerical results obtained through the finite element method (FEM) and have proved to produce results accurate enough to be of practical use, from the perspective of grasping general strength parameters in initial hull planning. Furthermore, we have performed hull structure weight optimization by combining these calculations with genetic algorithms, thereby additionally verifying their validity for the applications addressed here.

1. Introduction

Generally, analysis of a double bottom structure by means of FEM requires at least 1000 nodes. If the calculation concerns one hold model with side shell structure and transverse bulkhead, the number of nodes required increases to at least 5000.

The FEM may prove superior in exactness for a given external force, however it is an excessively time consuming method if used in the initial stages of hull planning. In these early stages any advantages which FEM offers in exactness are overcome by the fact that many of the dimension and parameter would be still indefinite. In many cases, present design characteristics would be used to approximate an equivalent double hull structure for examination via grid analysis.

This proposed approach to the evaluation of strength is aimed at quickening the time required for analysis by inputting the limited information available such as plate thickness or the arrangement of girders, and is not as accurate as the FEM.

And although structuring the analysis in this way is efficient in the initial planing stages to evaluate a strength on the whole and reinforcements necessary to provide, a complete detailed structural analysis should still be done in the later stages of design after basic parameters and details have become definite.

As to the validity of structuring our analysis in this way, we confirm its usefulness by comparing with theoretical values and the numerical results of FEM. Additionally, by applying genetic algorithms to the proposed method, we implement the weight optimization system for the double bottom structure.

2. Simplified method of analysis for combined double skinned structure

2.1 Summary of the Calculations

In this section we summarize the proposed calculation method and then present the examples of actual calculations. Three essential points of the calculations are discussed below.

1. Modeling the hold structure is accomplished using five structural elements and considering the double bottom structure to comprise one structural element for example.
2. Composition of double hull structures, such as bulk carriers, container ships and other such designs will be accomplished using the following three types of structural elements, each with its own unique deformation characteristics.
Principal structural elements (basic)

- Double bottom structure
- Vertical double skin structure
- Vertical single skin structure

3. Defining structural elements with series of functions which have a maximum number of twenty-five undefined deflection coefficients and applying the energy method of analysis. In this, we ensure continuity of rotation between the elements by applying Lagrange’s multiplier method.

Fig. 1 shows examples of this concept in modeling a bulk carrier and open bulk carrier. Fig. 2 shows a general flow of the calculations.

2.2 Application of Energy Method and Nondimensional Stiffness Matrix

As shown in the expression (1), we separate structural deflection into bending and shear deflection, expressing these with a series of separable functions.

\[ w(\xi, \eta) = w_{bd}(\xi, \eta) + w_{ds}(\xi, \eta) \]

\[ = \sum_{i=1}^{n} \delta f_i(\xi) f_i(\eta) \]  

(1)

Here, \( \xi \) and \( \eta \) indicate nondimensional expressions of coordinates as shown in Fig. 3, and suffix b and s denote bending and shearing respectively.

Functions \( f_i(\xi) \) and \( f_i(\eta) \) as shown in (1) above are defined as simple functions which do not incorporate influence of the adjoining structure and bending angle. In our notation, we characterize the function in \( \eta \) direction by adding a bar on top of function. As mentioned above, we guarantee continuity of rotation between structural elements with Lagrange’s Multiplier which will be discussed in greater detail later. The energy function may be explained as follows.

\[
K = V - T \\
= \frac{D_s}{2} \int_1^1 \int_1^1 \left[ A_i \left( \frac{\partial^2 w_{bd}}{\partial \xi^2} \right)^2 + A_i \left( \frac{\partial^2 w_{ds}}{\partial \eta^2} \right)^2 \\
+ A_i \left( \frac{\partial w_{bd}}{\partial \xi} \right) \left( \frac{\partial w_{bd}}{\partial \xi} \right) + A_i \left( \frac{\partial w_{ds}}{\partial \eta} \right) \left( \frac{\partial w_{ds}}{\partial \eta} \right) \\
+ A_i \left( \frac{\partial w_{bd}}{\partial \xi} \right) \left( \frac{\partial w_{ds}}{\partial \eta} \right) \right] d\xi d\eta \\
+ A_{10} \int_0^1 \left( \frac{\partial w_{bd}}{\partial \xi} \right)^2 d\eta \\
+ A_{10} \int_0^1 \left( \frac{\partial w_{ds}}{\partial \eta} \right)^2 d\xi - 4\pi A_i \int_0^1 \int_0^1 w d\xi d\eta
\]  

(2)

Fig. 1 Structural idealization

Fig. 2 Outline flow of analysis

Fig. 3 Structural model for Double Hull structure
Here, \( \lambda = l_2/l_1 \)

\( I_x, I_y \): bending or torsion rigidity of double hull structure.

When we express operations performed in (2) above, the following function is generally used.

\[
\sum_{i=1}^{n} \int \delta_i \delta_j [d \text{differential}] dy'dx
\]

\[
\sum_{i=1}^{n} \int \int \delta_i \frac{\partial}{\partial y'} \delta_j [d \text{differential}] dy'dx
\]

(4)

As for the function \( \alpha(\xi), \beta(\eta) \), from this point on, we shall express the differential as follows.

The following expression is usually applied with regards to external force.

\[
\sum_{i=1}^{n} \int f_i(\xi) d\xi \int f_i(\eta) d\eta = \sum_{i=1}^{n} \Delta_i P_i Q_i
\]

(5)

The energy function \( K = V - T \) will be expressed as follows by applying the functions (4) and (5).

\[
K = \frac{D_0}{2h_1 h_2} \sum_{i=1}^{n} A_i \sum_{j=1}^{n} \delta_i \delta_j [Z_{ij}]
\]

\[
- q_i h_i \sum_{j=1}^{n} \delta_i \delta_j [U_i]
\]

\[
s_{Z_{ij}} = s_{X_{ij}} s_{Y_{ij}}
\]

\[
U_i = P_i Q_i
\]

(6)

Taking function (6) to the extreme, the undefined vector of the deflection coefficient \( \delta_i \) is addressed as follows.

\[
\{ \delta_i \} = \frac{q_i h_i}{D_0} \left( [Z_{ij}]^{-1} \right) [U_i]
\]

(7)

\( s_{Z_{ij}} \) is the integral or products of a multiple of deflection function \( f_i(\xi), f_i(\eta) \) or their differentiated functions. Once we file results of the calculation of these functions we can calculate \( ZZ_{ij} \) by varying the stiffness ratio \( A_k \). We also can quicken the calculations by varying \( A_k \) many times as would be done in the process of structural optimization.

2.3 Application of Lagrange’s Multiplier Method to Double Hull Structures

Here, we explain the application of Lagrange’s multiplier method in order to maintain the deflection angle of the elemental joints in complex structures comprising multiple double hull structural elements (including single skin structural elements). The use of this method provides us not only with an unlimited number of structural elements, but also with various combinations of structural elements. We describe the process of analysis for the model having five structural elements shown in Fig. 4 by restricting the application to the general understanding of strength and weight optimization in the initial structural planning stages. Continuities of structural rotation are kept in six points.

When \( m \) indicates the number of structural elements, \( p \) denotes the position where the continuity of rotation is kept, and \( \Theta_p \) is the condition of rotation at each point \( p \). The energy formula including Lagrange’s multiplier \( L \) is shown in the following expression.

\[
K = V - T + L
\]

\[
V = \frac{1}{2} \sum_{i=1}^{n} D_i \sum_{j=1}^{n} \sum_{k=1}^{n} \delta_{ik} \delta_{jk} [Z_{ij}]
\]

\[
T = \sum_{i=1}^{n} \sum_{j=1}^{n} \delta_{ij} [U_i]
\]

(8)

The rotation \( \theta_i \) of \( \xi \)-axis (parallel to \( \eta \) axis) and the rotation \( \theta_i \) of \( \eta \)-axis (parallel to \( \xi \) axis) are given in the following expression.

\[
\theta_i = \frac{1}{l_i} \sum_{j=1}^{n} g_i(\xi) f_i(\eta) \delta_{ij} = \frac{1}{l_i} \left( \{ \xi \} \right) \left( \{ \eta \} \right) \delta_{ij}
\]

\[
\{ \xi \} = \{ g_i(\xi) f_i(\eta) \}
\]

\[
\{ \eta \} = \{ f_i(\xi) g_i(\eta) \}
\]

(9)

When the coordinates in the connection point are given in formula (9), the vectors of rotation \( \{ \xi \}, \{ \eta \} \), are given as the definite vector coefficients.
When we substitute the sequential condition, given in formula (8) for formula (10) and take the stationary point of K, the formula relative to the structural element m is given in the following expression.

\[
\begin{align*}
(\frac{D_x}{b_1})_m + & \sum_{i=1}^{l} \sum_{j=1}^{l} [m_{ZZij}]^{-1} (\hat{q}_{ij}) \sigma_i \mu_i \\
- \sum_{i=1}^{l} (1 - \hat{q}_{ij}) & \sum_{i=1}^{l} (\frac{1}{D_x})_m = 0
\end{align*}
\]  
(11)

Multiplying both the sides in formula (11) by \([m_{ZZij}]^{-1}\), the vectors of undefined deflection coefficient \(\{m_{\delta i}\}\) of the structural element m are given in the following form.

\[
\begin{align*}
\{m_{\delta i}\} = & - (\pm) \sum_{i=1}^{l} (\frac{1}{D_x})_m \sum_{i=1}^{l} \sum_{j=1}^{l} [m_{ZZij}]^{-1} (\hat{q}_{ij}) \\
+ (\pm) \sum_{i=1}^{l} (\frac{1}{D_x})_m \sum_{i=1}^{l} \sum_{j=1}^{l} [m_{ZZij}]^{-1} (\hat{q}_{ij}) \\
+ \sum_{i=1}^{l} (\frac{1}{D_x})_m \sum_{i=1}^{l} \sum_{j=1}^{l} [m_{ZZij}]^{-1} (\hat{q}_{ij}) \\
& \sum_{i=1}^{l} (\frac{1}{D_x})_m \sum_{i=1}^{l} \sum_{j=1}^{l} [m_{ZZij}]^{-1} (\hat{q}_{ij})
\end{align*}
\]  
(12)

The simultaneous equations in \(\hat{q}_{ij}\) are preceded by substituting formula (12) for formula (10). \([\varphi_{m}]\) is a symmetrical matrix.

\[
[\varphi_{m}] = [\varphi_{m}] = (\frac{1}{D_x})_m = 1 \cdots 6
\]  
(13)

When we apply formula (13), we calculate the constant given in the following expression. \([m_{ZZij}]\) is the function of stiffness.

\[
\begin{align*}
a_m & = \sum_{i=1}^{l} \sum_{j=1}^{l} [m_{ZZij}]^{-1} (\hat{q}_{ij}) \\
b_m & = \sum_{i=1}^{l} \sum_{j=1}^{l} [m_{ZZij}]^{-1} (\hat{q}_{ij}) \\
c_m & = \sum_{i=1}^{l} \sum_{j=1}^{l} [m_{ZZij}]^{-1} (\hat{q}_{ij}) \\
u_m & = \sum_{i=1}^{l} \sum_{j=1}^{l} [m_{ZZij}]^{-1} (\hat{q}_{ij})
\end{align*}
\]  
(14)

Expressing \([\varphi_{m}]\) and \([\psi_{m}]\) in formula (13) with formula (14), the following expression is produced.

\[
\begin{align*}
\{\varphi_i\} = \left[ \begin{array}{cccc}
\frac{\lambda}{D_x} a_1 + & \frac{\lambda}{D_x} a_2 & \frac{\lambda}{D_x} a_3 \\
\frac{1}{D_x} b_1 & 0 & 0 \\
\frac{1}{D_x} b_2 & -\frac{1}{D_x} b_1 & 0 \\
\frac{1}{D_x} b_3 & -\frac{1}{D_x} b_2 & 0 \\
\frac{1}{D_x} b_4 & -\frac{1}{D_x} b_3 & 0 \\
\frac{1}{D_x} b_5 & -\frac{1}{D_x} b_4 & 0 \\
\frac{1}{D_x} b_6 & -\frac{1}{D_x} b_5 & 0
\end{array} \right] \psi_i
\end{align*}
\]  
(15)

By substituting Lagrange’s multiplier vector \([\hat{q}_{ij}]\) in formula (13) for formula (12), the vectors of deflection coefficients \(\{m_{\delta i}\}\) for each of the structural elements are expressed as follows.
With \( \{w\} \delta \) in formula (17), the deflection function of each of the structural elements is defined and we can calculate a bending moment or sheering force by using formula (17).

### 2.4 Functions

The functions and differentials applying to double bottom structures, vertical double skin structures, and vertical single skin structures are described in Table 1, 2, and 3. Table 4, 5, and 6 show the distribution of functions to each undefined deflection coefficients.

The definition of nondimensional coordinates \( \xi, \eta, \eta \) is addressed in Figures 3, 5, and 6.

#### Table 3 Code number of functions for vertical single hull structure

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<th>function</th>
<th>symbol</th>
<th>( \eta ) direction</th>
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</tr>
<tr>
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<td></td>
</tr>
<tr>
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<td>8</td>
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<td>9</td>
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<td>( -30 + 60\eta^6 - 30\eta^8 )</td>
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<td>( -2 )</td>
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#### Table 4 Code distribution of functions for double bottom and vertical double hull structure

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<th>( \eta ) direction</th>
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<td>( 1 - \xi^2 )</td>
<td>5</td>
<td>( 1 - \eta^2 )</td>
</tr>
<tr>
<td>6</td>
<td>( 0 + 3\xi^4 + \xi^6 )</td>
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<td>( 6 - 12\eta^6 + 6\eta^8 )</td>
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<tr>
<td>7</td>
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<td>7</td>
<td>( 20 - 30\eta^6 + 15\eta^8 )</td>
</tr>
<tr>
<td>8</td>
<td>( 0 + 3\xi^4 + \xi^6 )</td>
<td>8</td>
<td>( -20 + 30\eta^6 - 15\eta^8 )</td>
</tr>
<tr>
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<td>13</td>
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<td>13</td>
<td>( -2 )</td>
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3. Comparison of Analytical Results with Theoretical values and Numerical Results

3.1 Comparison with Theoretical Results

Dr. M. Yamakoshi [1] gives the equation of equilibrium including shear effects on orthotropic plates, and obtains the effects of shear deformation on double bottom structures which are simply supported along four edges.

An actual double skin structure such as a double bottom is, however, supported elastically along its edges by adjacent structures and the elasticity of this support must, accordingly, be taken into consideration when evaluating the strength of a double skin structure.

From this perspective, our proposed method is actually an improvement over present methods in that it is much more applicable to actual ship hull design. This is because it takes into account not only the boundary effect on double skin structures but also shear effect, even though the proposed is an approximation method based on laws of energy.

However, for purposes of comparison, our proposed method can express boundary conditions constituting simple, four edge support by assuming infinitely small outplane rigidities in the adjacent structures and alternate loading on the double bottom.

Having performed the calculations using identical assumed conditions in this way, results of the proposed method have been compared very favorably with those of Yamakoshi.

Comparison of results obtained by our proposed method with the results by Yamakoshi are shown in Fig. 7 and Fig. 8. Fig. 7 shows in case of $\alpha_x=0.01$ and Fig. 8 in case of $\alpha_x=0.03$. In these, the shear effect is expressed in terms of an inversion number for non-dimensional shear rigidities.

As seen on these figures, results of our proposed method are in fairly good agreement with those by Yamakoshi. Definitions of the symbols in these figures are as follows.

\[
\alpha_x = \frac{D_s}{S_a a^2}, \quad \alpha_y = \frac{D_s}{S_b b^2}, \quad \lambda = \frac{b}{a}
\]  

(18)

3.2 Comparison with Numerical Results Obtained via FEM

Analysis was carried out for the structural model shown in Figure 9, setting boundary conditions both as having two edges simply supported / two edges fixed, and as having four edges fixed.

The combined double-hulled structures also shown in Figure 9 used idealized double skinned panels assigned the same boundary conditions as our FEM model by assuming the adjacent structures, such as side shell and transverse bulkheads, to have infinitely high or small outplane rigidities so as to accommodate the boundaries.

Calculations by our proposed method were then compared with the numerical results obtained by means of FEM. The comparisons are shown for deflection in...
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a) Deflection  
b) Bending moment  
c) Shearing force

**Fig. 7** Comparison of present method with theory on shear effect ($\alpha_x=0.01$)

**Fig. 8** Comparison of present method with theory on shear effect ($\alpha_x=0.03$)
Fig. 9  Structure model for FEM analysis

Fig. 10  Comparison of deflection (two edges simply support two edges fixed)

Fig. 11  Comparison of surface stress in skin plate (two edges support two edges fixed)

Fig. 12  Comparison of shear stress (two edges support two edges fixed)
Figure 10, stress on skin plates in Figure 11, and shear stress on girders or floor in Figure 12 for boundary conditions which assume two edges supported and two edges fixed. Similarly, the results are shown in Figures 13, 14 and 15 for the conditions which assume four edges to be fixed.


This summary is an elemental explanation of the process of structural stiffness evaluation as consolidated with optimization planning.

The standard of evaluation for the optimization will vary according to specific purposes. It may be the weight, the number of structural elements or the cost. In the case of a ship with double bottom, we have not found a method with which we can evaluate the final stiffness of a double hull structure any faster than those methods already in use.

![Graphs showing comparison of deflection and stress](image)

Fig. 13 Comparison of deflection (four edges fixed)  
Fig. 14 Comparison of surface stress in skin plate (four edges fixed)  
Fig. 15 Comparison of shear stress (four edges fixed)
It is, of course, possible to consolidate the numerical calculations by FEM into the optimization method. However, in early stages of initial hull design, while many elements are still undefined, it is preferable to pursue optimized hull planning though adoption of a more simple stiffness evaluation.

Accordingly, we have tried to optimize hull structure designs by using genetic algorithms through the method here suggested. The weight evaluation in this paper is limited to that of the double bottom structure.

4.1 Calculation Model

We applied genetic algorithms to the bulk carrier structure shown in Fig. 16 with its alternate loading to optimize the weights double bottom structures in loading hold. The calculation of optimization was carried out for the models having three kinds of torsional rigidities to the bilge hopper and bulkhead without stool for comparison. With respect to genes, we considered each independent variable as a single gene. For an objective function, we referred to the weight of the double bottom structure in a loading hold.

Where our factors may violate the required physical or mathematical conditions, we compensate for this by introducing penalty factors to the objective function, thereby eliminating these restrictions.

Each gene has a lower limit, an upper limit and a step value, such that each gene progresses from step to step in discrete intervals. Table 6 shows independent variables of this model and the set of lower limits, upper limits and steps for each variable.

The object of this process is limited to examination of the application of genetic algorithms to structural optimization in initial hull planning. Optimization of conditions in order to obtain optimum value is not within the confines of this discussion. Accordingly, the conditions are established by referring to a previous thesis[2],[3],[4],[5] as shown below.

Penalty coefficient: $C_p = 0.05$
Population size: $N_p = 50$
Crossover probability: $P_c = 0.8$
Mutation probability: $P_m = 0.001$
Number of alternate generations: $N_g = 80$

We added the six conditions below as the defined conditions. An adoption of HT 36 steel is assumed.

- Board thickness of shell and inner bottom $t_b \geq 3.65 \sqrt[0.72]{h} + 3.5$
- Section modules of longitudinal stiffener $Z \geq 7 \times 0.72sh^2$
- Stress of shell and inner bottom

Fig. 16 Structural model for weight optimization

Fig. 17 Weight optimization of double bottom structure
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4.2 Results of the Calculation

Fig. 17 shows the results of the calculation. This calculation required 80 generation changes with the $4.3 \times 10^9$ possible 32 bit binary combinations and a total of 4000 evaluations were performed. The time required to perform these calculation on a personal computer (Pentium Pro 200 MHz) was approximately 8 hours. According to our calculations, the optimum number of generation changes was about 20. We show the combinations of optimum results in Table 6.

5. Conclusion

In the preceding, we have illustrated a simplified calculation applying energy methods and Lagrange's multiplier method to the evaluation of strength for double hull structures in initial hull planning. The result is summarized below.

- It will take approximately 1 hours for a personal computer (Pentium Pro 200 MHz) to calculate the nondimensional elements of stiffness matrix against the three kinds of structural elements.

However, once we have completed this calculation, we will be able to find the analytic result immediately by extracting data from the file and multiplying stiffness in accordance with arbitrary combination of structural arrangement. It takes approximately 3 seconds for a personal computer (Pentium Pro 200 MHz) to obtain the results. (One calculation, one case.)

- We have found the results of these calculations to be in good agreement with the theoretical and numerical results obtained through FEM.

Accordingly, these results of calculation will be very useful for evaluation of strength in initial hull planning.

Furthermore, we examined its application in structural optimization, combining our analytical results and genetic algorithms. Our conclusions are summarized as follows:

- Genetic algorithms are appropriate methods for structural optimization, and are especially applicable to an optimization problem using multifarious discrete independent variables.

- Our analysis using this method required about 1 hours with 80 generation changes. This relatively small time consumption demonstrates the method to be an efficient tool with regard to structural optimization in initial hull structure planning.

References