6. Total System of Analysis on the Longitudinal Strength of Ships

—on the Longitudinal Strength of Oil Tankers—

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Summary

In this paper, an outline is presented of the total system of computer programme that has been developed by Nippon Kaiji Kyokai for the rational and direct evaluation on the longitudinal strength of hull girder of oceangoing vessels.

This system is consist of an integrated group of individual grogrammes which include an input data processing and automatic generating programme as well as those concerned with the theoretical analysis on the oscillating motion of ships among waves with use of strip method, structural analysis and stress calculations of hull girders based upon the general bending, and torsion theory of thin walled beams, and the statistical analysis on the fluctuating stresses in longitudinal members of the ship. The output of the computations gives a direct information on the probability of exceeding a certain prescribed value of the stresses caused in the longitudinal members during the whole life time of the ship.

Then, a discussion is made into the detail of a series of calculations which are performed on the longitudinal strength of existing oil tankers, of which the deadweight capacity varies from 50,000 to 500,000 tons. It is found from this analysis, that the fluctuating stresses in the longitudinal strength members due to vertical bending of hull girders are almost in the same level among these ships, whereas those due to horizontal bending of the hull girders show a gradual rise with increase of the size of the ships.

1. Introduction

Evaluation of reliability of a strength of ship structure and establishment of design criteria must be based on a rational and synthetic structural analysis of the ship as well as on the results of experience of ship's operation. For that purpose, first of all it is necessary to estimate accurately the stresses occurring in the structural members of a ship due to fluctuating wave loads during her navigation in ocean, and it is needed to develop such computer program as well directly as well as easily realize such purposes.

As a recent trend, on the other hand, the computer programs of this kind have been developed by the ship classification society of each country and presently the strength of ship structure is being examined synthetically by using such programs[1-6]. Likewise in

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Nippon Kaiji Kyokai, a computer program has been completed as a part of the research project for the development of a total system of computer programs for ship structural analysis[7)8)]. Refining on the method of the analysis currently employed on the longitudinal strength of ships, completion of this computer program has made it possible to realize the rational and consistent evaluation on the stresses caused in ship's hull girder.

In this system, firstly the theoretical analysis on the oscillating motions of the object ship under regular waves is performed and the fluctuating wave loads acting on the hull girder are obtained. Next, the fluctuating stresses caused under fluctuating loads in the longitudinal members of the ship are calculated based on the general bending and torsion theory, and then statistical analysis is performed with use of given wave spectrum and observation data on ocean irregular waves.

In the present paper, outline of the system and problems on the analysis are introduced and a discussion is made on the result of a series of calculation which are performed on the longitudinal strength of existing oil tankers by using this program.

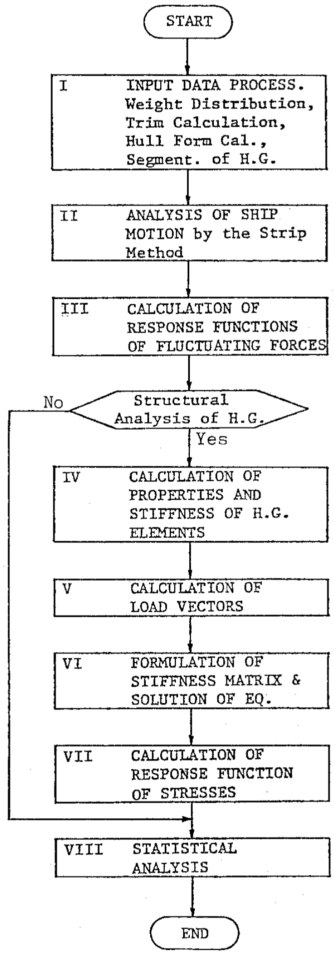

Fig. 1 Process Flow Chart of the System

2. Outline of the System

General process flow chart of the total system of analysis is shown in Fig. 1. The computer program of the system is written for use of the medium size computer FACOM 230-25 of which the core memory is 131 KB.

2.1 *Input Data Processing*

The input data processing program as indicated in step I of Fig. 1 basically consist of two parts, i.e. data generator for the analysis of ship motion and that for the structural analysis of hull girder.

2.1.1 *Data Generator for Ship Motion*

Analysis on the motions of ships is based on the strip method. The input data and their processing procedure are as follows.

(a) Necessary input data on the division of the strip is the ship's length only. The hull is equally subdivided into twenty strips between perpendiculars, and if additional data are provided, two strips afterward A.P. and one strip foreward F.P. may be added.

(b) Weight distributions and off-set table of the hull form are given as input data. Then the equilibrium condition of the ship under still water is determined by fundamental calculations on the trim.

(c) Each cross section of the strips is generally transformed into Lewis form. As for a specially shaped cross section which can hardly be transformed into Lewis form such as a part of bulbous bow, it is modified to that having equal cross sectional area.

(d) With use of the result of trim calculation and the off-set table, the necessary data are generated of the cross sectional area, draft and the half breadth of water plane of each strip.

(e) Vertical height of the center of gravity KG is given as input data. Moment of inertia for pitching and yawing is generated in the program, while that for rolling is to be given by manual input data for each strip.

(f) When consider non-linearity of rolling of ship, input data are to be given on the bilge keel.

2.1.2 *Data Generator for Structural Analysis*

As for the input data for structural analysis, consideration has been so given as it would be sufficient enough only for basic scantling of the hull girder to be transferred from construction drawings. The input data and their processing procedures are as follows.

(a) The hull girder is simulated as a continuous beam with variable cross sections, and the full length of which is divided into certain numbers (maximum 30) of beam element with uniform cross section. The hull girder will be automatically divided by giving, as input data, the number of division and the cross section patterns.

(b) Position or co-ordinate along the longitudinal direction of the ship to indicate the specific cross section, location of the structural members to be analysed are given by frame number.

(c) Cross sectional properties of the beam element are calculated by finite element method, and mesh division in each cross section of the beam element is automatically generated for a given pattern of cross section such as cargo tank part of oil tankers, where only the basic dimensions and scantlings transferred from construction drawing are needed as input data.

(d) As for input data for the mesh division of the cross section in fore and after ends of the ship, the sectional properties of the beam elements are determined by simply multiplying the values for midship part by appropriate ratio depending on the location of the cross section and on existence of the deck opening.

2.2 *Analysis of Ship Motion*

The second step in the system is the analysis on the ship motion based on the strip method as indicated in step II of Fig. 1. In this analysis the motion of ship due to each component wave is calculated for given values of the parameters such as ship's speed, angle of encounter with the component wave, length of the wave respectively, and accordingly the response functions of ship's motion for regular wave of unit wave height are obtained. When considering the non-linear characteristics of rolling angle vs. wave height, the response functions are calculated for each regular wave of certain prescribed values of wave height.

2.3 *Response Function of Forces*

Next step of the analysis is the calculation of response functions of forces caused by the ship motion among regular waves. From the results of the analysis of ship motion, distribution of fluctuating forces acting on each strip are obtained as summation of fluid force and inertia force, and then resultant forces in each cross section are determined by integrating the distributed loads over the whole surface of the strip.

2.4 *Calculation of Stiffness Coefficients for Structural Elements of the Hull Girder*

For the purpose of tortional bending analysis of hull girder, the stiffness matrixes of the beam elements are formulated by calculating their cross sectional properties such as locations of geometrical center of gravity and of shear center, etc.

2.5 *Calculation of Load Vectors*

Equivalent nodal forces are converted from the fluctuating forces obtained in step III, and they are applied as concentrated loads at each joint of the beam element.

2.6 *Structural Analysis of the Hull Girder*

The stiffness matrix of the hull girder is formulated by superposing the matrixes of the beam elements. Then, a matrix equation is introduced with a set of the prescribed load vectors obtained in step V and is solved for unknown vectors of the nodal displacement at the joints. It should be mentioned here that the matrix equation must be solved for a large number of load vectors amounting to the total numbers of the calculations as mentioned in 2.2, and therefore, the decomposed stiffness matrix is stored in core memory while the load vectors are read repeatedly 10 by 10 from auxilially memory of the system.

2.7 *Calculation of Response Function of Stresses*

Fluctuating stresses at certain prescribed location in the hull girder are calculated from the nodal displacement obtained in the above step, and their response function is formulated for any required points.

2.8 *Statistical Analysis*

Statistical analysis is then performed by using the results obtained in former steps on the response functions for ship motion, resultant forces in cross section, amplitude of the fluctuating stresses and so on. Short term distributions and probabilities of exceeding a certain prescribed level of each response are obtained with use of given wave spectrum and observation data on ocean waves.

3. Outline of the Method of Analysis

3.1 *Ship Motion and Fluctuating Load*

In the analysis of ship motion and fluctuating load, the strip method is applied in the system which has recently come into widely practical use. Ship motions of 6-degrees of freedom in 3-dimensional space are divided into the following three independent groups of oscillating motions;

(1) heaving (ζ) and pitching (ϕ),
(2) swaying (η), yawing (ψ) and rolling (θ),
(3) surging (ξ). (see Fig. 2)

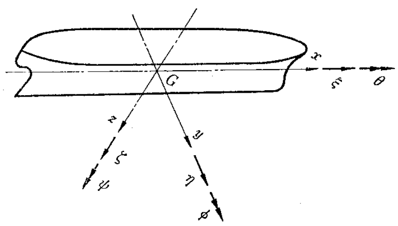

Fig. 2 Notation of Ship Motion and Coordinates Employed

For each group, analysis is made by considering coupling effect of each motion of ship. Since the analysis on the vertical motion of ship has been studied for long time, usefulness of the strip method has been well confirmed by comparing with actual phenomena of ships. In this system, therefore, Fukuda's linear strip method[9][10] is used for the analysis of heaving and pitching of the ships.

The analysis on the horizontal and rolling motion of ships is more difficult than that for vertical one because of the damping resistance due to viscous effect in addition to the wave making resistance as in the case of heaving motion. In this system, the extinction in rolling oscillation is defined by the following relation; $\Delta\theta = a\theta_m + b\theta_m^2$, where θ_m is mean amplitude of rolling and the coefficients a and b are derived from Watanabe and Inoue's method[11]. On the basis of above procedure, rolling resistance is represented as $A\dot{\theta}$ when rolling amplitude is θ. Above representation is linear form, but equation of motion becomes non-linear differential equation since the factor A is function of θ. In this system, Tasai's strip method[12] is applied with above mentioned non-linear modification. Careful attention must be paid to that, on the influence of ship speed and damping coefficient further research has to be made so that correspondence to actual phenomena should appear as good as in the case of vertical motion system. As for the third uncoupled surging motion, Motora's method based on only Froude-Kriloff hypothesis is applied in which added mass has been neglected. On this hypothesis, neither damping force nor restoring force is neglected, and therefore application of this method in the case of long period of wave encounter gives an unsuitable result. In this execution of the analysis, carefull attention is paid so as to avoid such condition in each case.

In the next place, outline of the procedure on analysis of fluctuating load in a regular wave is given below.

Fluctuating load per unit length acting on a strip, dF/dx, is represented as the summation of fluid force dF_f/dx and inertia force dF_i/dx. The fluid force dF_f/dx is determined by the form of cross section under water plane, period of wave encounter, ship motion and others, and they are calculated to fairly good approximation except by those errors due to the conversion into Lewis form. As to the inertia force dF_i/dx, however, it is very difficult to obtain exact distribution of weight and moment of inertia about rolling motion in lengthwise direction of ship. Ordinarily, in the case of longitudinal strength calculation, each distributed weight is approximated as a trapezoid. This method is applied in this analysis, piling up each trapezoid to get longitudinal weight distribution. (see Fig. 3)

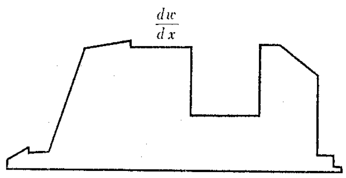

Fig. 3 Longitudinal Distribution of Weight

Vertical and horizontal distribution of weight is needed to get longitudinal distribution of moment of inertia about rolling motion. If such data are not available, following estimation will be used as moment of inertia for rolling motion per unit length about given longitudinal co-ordinate x.

$$\frac{di}{dx}=\frac{\dfrac{dw}{dx}\cdot B(x)\cdot D(x)}{\displaystyle\int \frac{dw}{dx}\cdot B(x)\cdot D(x)\cdot dx}\cdot I_r \qquad (1)$$

where $B(x)$ and $D(x)$ are breadth and depth of the section at x respectively, and I_r is moment of inertia for rolling motion about whole ship.

When wave forces in arbitrary cross section, consisting of six components (shearing force, bending moment etc.) are needed, they will be obtained by integrating above mentioned dF/dx from aft or fore end to given x.

3.2 *Structural Analysis of Hull Girder*

The purpose of the structural analysis of this system is to obtain structural response of the ship's hull subjected to fluctuating loads which are obtained from the ship's motion caused in many regular waves with parameters of ship's speed, angle of encounter and wave length being varied.

It is therefore necessary to solve the stiffness equation of the hull girder for a large number of the load vectors and accordingly in-core data handlings essentially needed for efficient processing of stiffness matrix by electronic computer.

Taking advantage of the reduced degree of freedom, a modified method of the finite element analysis based on the general bending theory for thin walled beams proposed by Kawai[13] has been used in this system. In this method, the ship structure is simulated as a continuous beam with variable cross sections and full length of the beam is divided into certain numbers of beam element with uniform cross section as indicated in Fig. 4

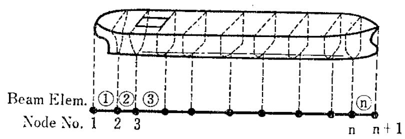

Fig. 4 Beam Element Division of Hull Girder

and then displacement method of analysis on the bending and torsion of continuous beam is applied considering deformation due to axial thrust, shearing force and bending as well as warping tortional displacement.

In this method, displacement functions, U, V and W in the transverse section of the beam element are assumed as follows:

$$\left.\begin{aligned} U(x,y,z)&=u(z)-y\cdot\theta(z)\\ V(x,y,z)&=v(z)+x\cdot\theta(z)\\ W(x,y,z)&=w(z)-x\cdot u'(z)-y\cdot v'(z)\\ &\quad+\theta'(z)\cdot\omega_n(x,y)\end{aligned}\right\} \qquad (2)$$

where $u(z)$, $v(z)$ and $w(z)$ are displacement at the centroid of the section in x, y and z

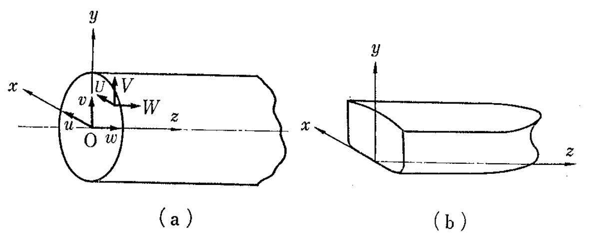

Fig. 5 Notation of Displacement and Coordinates Employed

direction respectively (see Fig. 5(a)); while $\theta(z)$ is the angle of rotation. $\omega_n(x, y)$ is the normalized warping function of St. Venant's torsion problem and is obtained by finite element technique[15] with use of plate element. Then, various sectional properties of each beam element such as St. Venant's torsional stiffness and warping torsional stiffness are evaluated in this program.

The displacement functions of the beam element along axial direction are assumed as polynominal of the 3rd order as follows:

$$\left.\begin{aligned} u(z)&=a_0+a_1z+a_2z^2+a_3z^3\\ v(z)&=b_0+b_1z+b_2z^2+b_3z^3\\ \theta(z)&=c_0+c_1z+c_2z^2+c_3z^3\\ w(z)&=d_0+d_1z \end{aligned}\right\} \quad (3)$$

Stiffness matrix of the beam element (14 by 14) can be obtained by using the above mentioned displacement functions in which the degrees of freedom are taken such as lateral and vertical displacements and rotations, angles of torsion and warping and axial displacements at both ends of a beam element. Details of this method are fully explained in the reference[16].

The number of division into the beam element must be appropriate enough so that hull girder which is a continuous beam with variable cross section can suitably be idealized as well as the solution can be obtained with a sufficient accuracy. In addition to these, the dimension of the formulated stiffness matrix must be within such limits that in-core data handling is possible as mentioned in the foregoing. The maximum number of beam element to be divided is 30 in this program. In this case, the size of the stiffness matrix is 217 with band width of 14, and computation with double precision can be performed within 131 KB core memories of electronic computer. The maximum number of load case which can be solved simultanuously in the matrix equation is 10 (the number of load vectors composed of amplitude and phase is 20). The above mentioned number of division of beam element is sufficient to obtain accurate result from practical view point of longitudinal strength analysis of hull girder.

As this analysis is based on a torsional bending theory of a beam, distribution of the shearing stress in the cross section due to external shear force can not be obtained. In this program, although each structural component in the hull girder is assumed to behave as a part of beam element, cross decks and deck girders in ships with large deck openings or multi-row hatches like container ships deform complexly, not simply as a single unit beam of the main hull girder. Further improvement should be made in the program to evaluate suitable value of the stiffness of hull girder for such kind of ships.

3.3 *Response Function of Fluctuating Stress*

Fluctuating loads obtained by the analysis on ship motions in 3.1 are given in terms of amplitude and phase, both of which being varied in each component of the load and at joints of hull girder. It is therefore necessary to analyze the structural response by taking into consideration the phase lag effect. When fluctuating load $\boldsymbol{F}$ (amplitude f and phase of a component) is imposed on joints of hull girder, joint displacement $\boldsymbol{d}$ (amplitude d and phase of a component) is expressed by the following relation, where $\boldsymbol{A}$ (a being a component) is inverse of stiffness matrix of hull girder.

$$\boldsymbol{d}=\boldsymbol{A}\cdot\boldsymbol{F} \quad (4)$$

It is otherwise read as

$$\begin{Bmatrix} d_1\cos(\omega_e t-\varepsilon_{d1})\\ d_2\cos(\omega_e t-\varepsilon_{d2})\\ \vdots\\ d_n\cos(\omega_e t-\varepsilon_{dn}) \end{Bmatrix} = \begin{bmatrix} a_{11}a_{12}\cdots a_{1n}\\ a_{21}a_{22}\cdots a_{2n}\\ \vdots\\ a_{n1}a_{n2}\cdots a_{nn} \end{bmatrix} \begin{Bmatrix} f_1\cos(\omega_e t-\varepsilon_{f1})\\ f_2\cos(\omega_e t-\varepsilon_{f2})\\ \vdots\\ f_n\cos(\omega_e t-\varepsilon_{fn}) \end{Bmatrix} \quad (4')$$

where ω_e is circular frequency of ship's encounter with wave, and n is total degrees of freedom. With regard to a component of displacement, it is expressed as follows.

$$d_k\cos(\omega_e t-\varepsilon_{dk})=\sum_{j=1}^{n} a_{kj}f_j\cos(\omega_e t-\varepsilon_{fj}) \quad (5)$$

Composing up each term in the righthand side of Eq. (5), the amplitude and the phase of a component of displacement at joints of hull girder are expressed as follows.

$$\left.\begin{aligned} d_k &= \sqrt{\left(\sum_{j=1}^{n} a_{kj} f_j \cos \varepsilon_{fj}\right)^2 + \left(\sum_{j=1}^{n} a_{kj} f_j \sin \varepsilon_{fj}\right)^2} \\ \varepsilon_{dk} &= \tan^{-1}\left(\frac{\sum_{j=1}^{n} \alpha_{kj} f_j \sin \varepsilon_{fj}}{\sum_{j=1}^{n} a_{kj} f_j \cos \varepsilon_{fj}}\right) \\ &\qquad : \sum_{j=1}^{n} a_{kj} f_j \cos \varepsilon_{fj} \geqq 0 \\ &= \tan^{-1}\left(\frac{\sum_{j=1}^{n} a_{kj} f_i \sin \varepsilon_{fj}}{\sum_{j=1}^{n} a_{kj} f_j \cos \varepsilon_{fj}}\right) + \pi \\ &\qquad : \sum_{j=1}^{n} a_{kj} f_j \cos \varepsilon_{fj} < 0 \end{aligned}\right\} \quad (6)$$

Further, from the displacement calculated as above can be obtained stresses in a certain location of a certain cross section of hull girder (axial stress, longitudinal bending stress, horizontal bending stress and warping stress). And furthermore as to the total longitudinal stress obtained by composing these stresses, it can be obtained as well by taking same procedure as above, considering phase difference among components.

3.4 *Statistical Analysis*

From the amplitudes of responses of ship in regular waves (fluctuating stress in longitudinal members, ship motions, resultant forces in cross section etc.) which were obtained by the calculation as a forementioned, their short-term distribution is calculated by using energy spectrum method. Then, with statistical data of waves in use, the long-term probability of extream values of these responses is calculated as for wave spectrum, the following ISSC-1970 spectrum[17] is used, and the statistical data of waves on significant wave height and mean wave period given by Walden or by Hogben are used.

$$[f(\omega, x)]^2 = 0.11 H^2 \omega_1^{-1} (\omega/\omega_1)^{-5} \times \exp[-0.44(\omega/\omega_1)^{-4}] \cdot 8/(3\pi) \cos^4 x \quad (7)$$

Furthermore, in case of rough sea, artificial speed reduction by maneuvering as well as natural speed down due to increase of resistance are likely to occur, and therefore these speed reductions have also been taken into account on making statistical analysis.

In this case, corelation between Beaufort scale and speed reduction as indicated in Fig. 6 have been used, which have been prepared by the Society investigating logbook of large exclusive vessels related with their navigating conditions at rough sea.

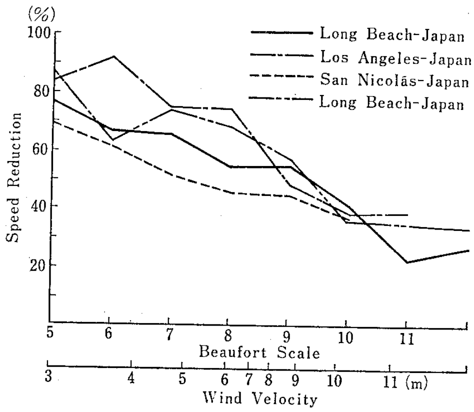

Fig. 6 An Example of Speed Reduction vs. Beaufort Scale

On the other hand, the corelation between Beaufort scale and significant wave height is given by ISSC-1970 report, and therefore, the responses of ship which have been calculated for several case of ship speed corresponding to a significant wave height, are statistically analyzed.

4. Analysis of Longitudinal Strength of Oil Tankers

4.1 *Series of Calculations on Oil Tankers*

A series of calculation are performed on twelve oil tankers of which the deadweight capacity varies from 50,000 tons to 500,000 tons and principal dimensions are shown in Table 1. In these analyses, the maxima exceeded during 10^8 cycles of wave encounter in the North

Table 1 Principal Dimensions of Ships Analyzed

Ship Name	(m) L × (m) B × (m) D × (m) d	(ton) DW	(ton) Δ	C_b	(kt) V_s	L/B	L/D	B/D	Longitudinal Bending Stress in Still Water (Midship) kg/mm² $B\underline{m}$	$D\underline{K}$
A	205.06×30.50×15.80×12.237	50,839	62,747	0.797	16.5	6.72	12.98	1.93	3.4	−3.9
B	213.00×32.00×16.90×12.993	60,584	73,023	0.804	15.5	6.66	12.60	1.89	6.9	−7.9
C	230.00×35.30×18.00×12.489	70,891	85,919	0.814	15.3	6.52	12.78	1.96	1.6	−1.9
D	346.00×40.20×21.80×15.101	103,690	121,110	0.799	15.6	6.12	11.28	1.84	5.2	−5.9
E	260.00×43.50×22.80×17.032	138,539	160,771	0.815	15.4	5.98	11.40	1.91	0.8	−1.0
F	270.00×44.00×25.00×17.833	155,455	179,949	0.829	14.8	6.14	10.80	1.76	4.3	−5.1
G	281.00×46.20×25.00×17.034	157,825	183,138	0.840	16.1	6.08	11.24	1.85	−1.2	1.4
H	302.00×50.40×24.30×18.436	204,540	236,250	0.814	16.1	5.99	12.43	2.07	0.3	−0.3
I	314.00×54.80×26.40×20.530	261,354	297,960	0.825	15.8	5.73	11.89	2.08	1.1	−1.3
J	326.00×49.80×23.20×17.685	209,413	241,881	0.830	16.5	6.55	14.05	2.15	5.3	−6.4
K	330.00×54.50×35.00×27.074	372,698	425,674	0.853	15.0	6.06	9.43	1.56	3.9	−4.6
L	360.00×62.00×36.00×28.000	477,000	547,301	0.852	14.7	5.81	10.00	1.72	2.2	−2.5

Atlantic in winter, with wave data of Walden[18] in use, are calculated for ship motions, moments, forces and stresses in the fully loaded condition at service speed of ships.

The moment of inertia for the rolling of ships is obtained from the formula given by Kato[19]. The N-coefficient for ship motion is modified by the method of Fukuda and others[10], taking account of influence of the speed of ships. In the strength analysis of the hull girders, the hull girders are divided analysis of the hull girders, the hull girders are divided into thirty beam elements in the direction of ship length.

4.2 *Results and Reviews*

4.2.1 *Bending moments*

The maximum expected value during 10^8 cycles of wave encounter on the vertical bending moments (M_X) and horizontal bending moments (M_Y) acting on the midship of the twelve ships analyzed are shown in Fig. 7, where the values are plotted against cubic root of the full load displacement of each ship, from ship A to ship L. Non-dimensional expression are used in the figures, namely M_X divided by $\rho g L^3 B$ in Fig. 7(a), and M_Y divided by $\rho g L^3 B$ or $\rho g L^2 BD$ in Fig. 7(b).

As seen from Fig. 7(a), the values of

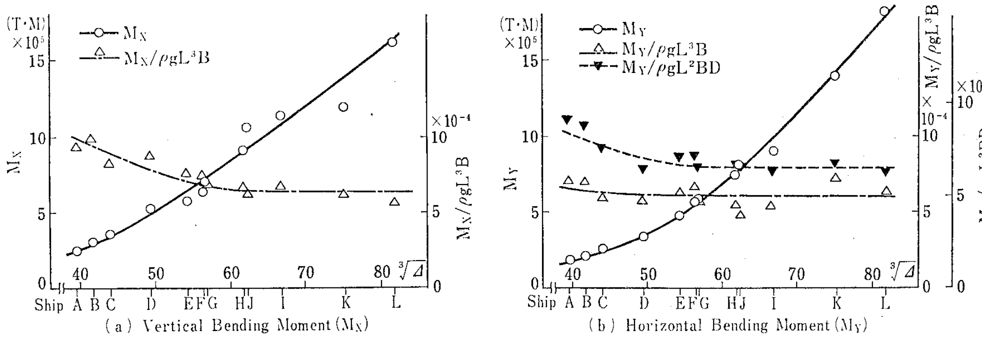

Fig. 7 Midship Wave Bending Moments (Maxima exceeded during 10^8 cycles in the North Atlantic Winter, All heading)

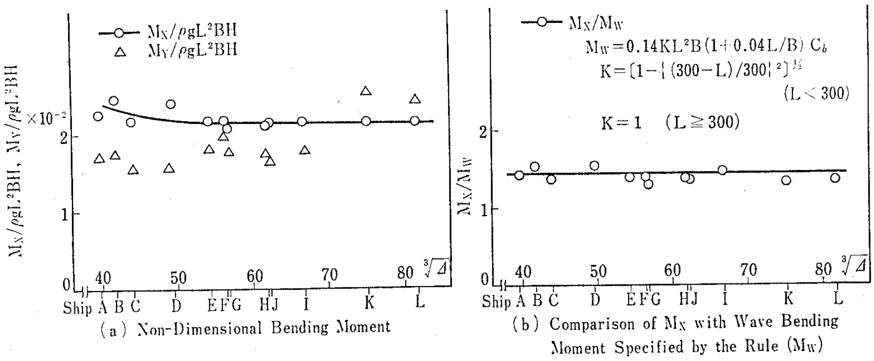

Fig. 8 Midship Wave Bending Moments (Maxima exceeded during 10^8 cycles in the North Atlantic Winter, All heading)

$M_X/\rho g L^3 B$ gradually decrease according to the size of ships of which the deadweight capacity is less than 100,000 tons and the values are nearly constant and less scattered in the larger ships. While on the other hand, from Fig. 7(b) values of $M_Y/\rho g L^3 B$ fall in the range of 5×10^{-4} to 7×10^{-4} but the scattering of values is larger than those of M_X. Specially, on the ships of J and K having different ratio of L/D and B/D compared with the other ships, the scattering is seemed to be larger than the others. From this reason, the non-dimensional values of $M_Y/\rho g L^2 BD$ having L^2BD as a denominator instead of L^3B, have been examined. In this case, the scattering of value is smaller than in the former case and the values of $M_Y/\rho g L^2 BD$ are similarly distributed as the values of $M_X/\rho g L^3 B$ in Fig. 7(a). From these results, it could be presumed that the forces concerning to the horizontal bending moments are related to the values of D or d as well as L or B.

Now here is made examination on the bending moments thus obtained in the above, comparing them with the bending moments in waves deduced from the equivalent wave height which is conventionally in use for the ship's design and the bending moments in waves as specified by the Ship Classification Societie's Rules.

The non-dimensional values of M_X and M_Y divided by $\rho g H L^2 B$ are shown in Fig. 8(a). Here, H is the equivalent wave height to be obtained from the following formulae which were previously used as the bases of the longitudinal strength calculation in the construction rule of NIPPON KAIJI KYOKAI.

$$\left.\begin{aligned} H&=0.61L^{1/2} & &(L\leqq 150\,\mathrm{m})\\ &=1.41L^{1/3} & &(150\,\mathrm{m}<L\leqq 250\,\mathrm{m})\\ &=2.23L^{1/4} & &(250\,\mathrm{m}<L\leqq 300\,\mathrm{m})\\ &=9.28 & &(300\,\mathrm{m}<L)\end{aligned}\right\}\qquad (8)$$

The values of $M_X/\rho g H L^2 B$ fall within the narrow range corresponding to the size of ships, but the values of $M_Y/\rho g H L^2 B$ are scattered. This scattering seems to be natural, as the equivalent wave height (H) is determined by considering only the vertical bending moment of the ships.

Further, the non-dimensional values of M_X divided by the vertical bending moment in waves M_W which is used in the Rules of NIPPON KAIJI KYOKAI are shown in Fig. 8(b). The values of M_W are given by the following formula.

$$M_W=0.14KL^2B(1+0.04L/B)C_b \qquad (9)$$

where

$$\begin{aligned} K&=[1-\{(300-L)/300\}^2]^{1/2} & &(L<300\,\mathrm{m})\\ &=1.0 & &(L\geqq 300\,\mathrm{m})\end{aligned}$$

As can be seen from Fig. 8(b), the values of ratio M_X/M_W are closely situated on a same level for those ships and thus the vertical bending moments (M_X) calculated by this system are in good correspondence to those (M_W) specified in the Rules. The values of M_X/M_W are more or less 1.4 fairly deviating from 1.0, which is attributable to the reason that the bases for the calculations of M_X and M_W are different, or in other words M_X is the 10^{-8} extreme characteristic value in the short crested waves with all heading angles, while M_W is the 10^{-5} extreme characteristic value in the long crested waves with the constant heading angle.

4.2.2 *Stresses*

The extreme characteristic values of the fluctuating normal stresses, such as axial stress (σ_a), vertical bending stress (σ_{bX}), horizontal bending stress (σ_{bY}), warping stress (σ_w) and total stress (σ_n) with these stress components combined taking account of phase difference in each stress component, which are caused at the position of deck centre line, gunwale part, bottom centre line and bilge part of the midship section, are calculated and shown in Figs. 9(a) to (d) samewise as in Figs. 7 and 8.

From Figs. 9(a) to (d), the vertical bending stresses are seen on the same level with a small variation irrespective of the size of ships. From this result, the ships analyzed in this paper may be deemed having almost same longitudinal strength capability concerning to the vertical bending. While on the other hand, the axial stresses rise gradually as the displacement of ships increases, such increase of the stress is small and the difference of the stress between ship A and ship L is about $0.6\,kg/mm^2$.

As the component of horizontal bending stress and warping stress vanishes on the centre line of ships, the relation between the vertical bending stresses, axial stresses and the combined total stresses (σ_n) can be examined by comparing Fig. 9(a) with Fig. 9(c). As seen from these figures, σ_n is smaller than σ_{bX} on the bottom and σ_n is larger than σ_{bX} on the deck, and the difference of these stresses is about equal to the axial stresses. Such outcome is due to the reason that those stress components which are induced by the vertical bending stress and the axial stress having their phase same on the deck and opposite on

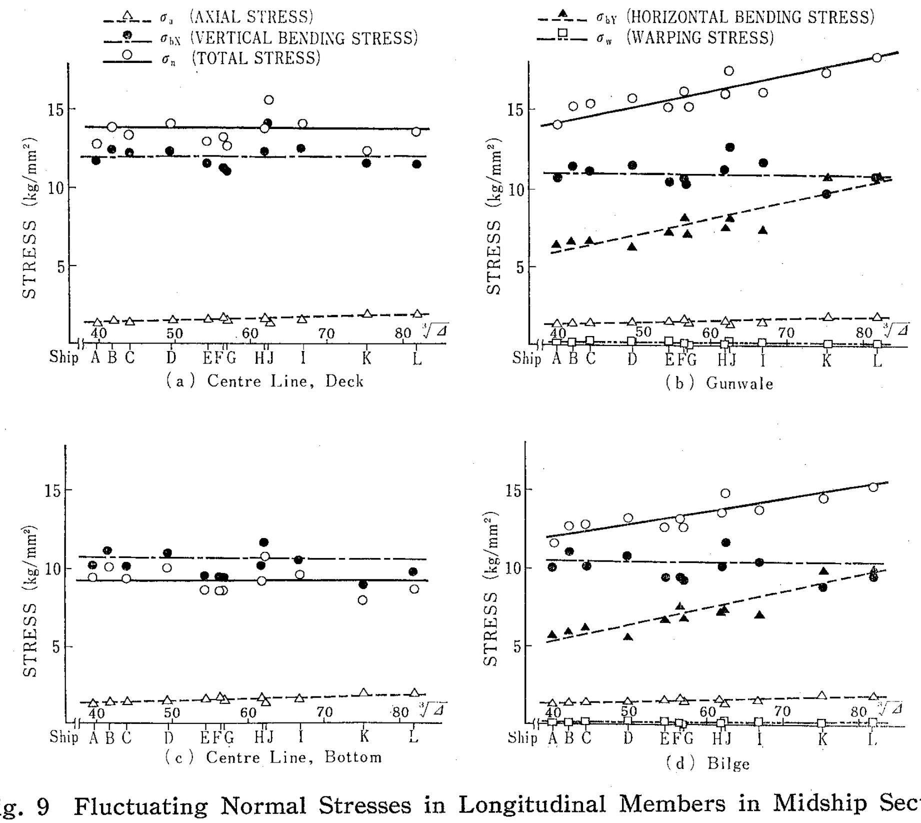

Fig. 9 Fluctuating Normal Stresses in Longitudinal Members in Midship Section

the bottom, are being dominative.

From Figs. 9(b) and (d), the horizontal bending stresses are seen rising as the displacement of ships increases and thereby the strength of ships for horizontal bending is comparatively on decrease according to the increase of the size of ships. The combined total stresses also rise according to the increase of the size of ships being affected by the horizontal bending stresses, and the stresses of the gunwale part are larger than those of the bilge part due to the same reason as mentioned above on the difference of the stresses of the bottom centre line and the deck centre line.

As for those ships having the close section like oil tanker, the warping stresses are very small without relation to the size of ships.

For reference, the vertical bending stresses in the still water on the bottom centre line and the deck centre line of the midship section are shown in Table 1.

5. Conclusion

In this paper, in the first place a summary on the construction and functions of the total system for the analysis on the longitudinal strength of ships has been presented, and then the analytical method of each part of the system have been briefly described. For further study and improvement of the analysis, it would be necessary to continue to examine and revice the system so as to be in conformity with the advance of study especially in the field of analysis on the horizontal motion of ships.

Improvement of the system is also left in the structural analysis when these method are applied with sufficient accuracy for the ships with large deck openings such as container ships. Furthermore, they must be extended up to such level as to even connect with an estimation on the ultimate strength of ships as well as the design criteria of ship structures, and thus reach completion of the so-called total system in the future.

Then, in this paper, the results of the series calculations have been discussed on the longitudinal strength of large tankers by using this program. As a result of this investigation, it has become evident that while the vertical bending stresses σ_{bX} are on the same level irrespective of the size of ships, the horizontal bending stresses σ_{bY} tend to increase as the size of ships become large so far as the calculations herein are concerned. This fact shows that the horizontal bending should be taken into account when estimating the longitudinal strength of ships.

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