Design Loads Used for Direct Strength Assessment of Merchant Ship Structures

By Tingyao Zhu and Toshiyuki Shigemi**

ABSTRACT

This paper summarizes the results of extensive research on the design loads used for strength assessment of various merchant ship structures such as tankers, bulk carriers, and container ships. The main aim of the research was to develop practical methods for estimating design loads acting on primary structural members of tankers, bulk carriers, and container ships based on rational technical backgrounds.

In this study:

1) *Design sea states that closely resemble the actual sea states which are considered as being the most severe for hull structures are proposed.*
2) *Practical methods for estimating the design sea states are proposed based on parametric studies using the results of series calculations on representative merchant ships.*
3) *Practical methods for estimating design regular waves that result in the same level of stresses as that induced in irregular waves under design sea states are proposed.*
4) *Practical methods for estimating design loads such as ship motions, accelerations, hull-girder bending moments, and hydrodynamic pressures that are induced under design regular wave conditions are briefly introduced.*

The findings in this study have been summarized and implemented in new design standards for tanker, bulk carrier, and container ship structures (Guidelines for Tanker Structures, 2001, Nippon Kaiji Kyokai; Guidelines for Bulk Carrier Structures, 2002, Nippon Kaiji Kyokai; and Guidelines for container Carrier Structures, 2003, Nippon Kaiji Kyokai).

***Keywords**: Tanker structures; Bulk carrier structures; Container ship structures; Strength assessment; Design sea states; Design regular waves; Design loads*

1. INTRODUCTION

The strength of ship structures is generally evaluated by setting design loads, performing structural analysis using these design loads, and by assessing yielding, buckling and fatigue strength using the results of the structural analysis. In this sequence of strength assessment procedures, the setting of design loads comes first. Thus, the accuracy of the design loads is considered to be an extremely important requirement, especially since it significantly influences the final structural scantlings and the safety of the ship structure. Furthermore, design loads should be closely linked with design conditions or operating conditions related to hull structural strength, and should always be referenced over the entire service life of a ship starting with the design stage, through construction, operation, and finally the scrapping of the ship.

However, most of the design loads currently proposed are used as standard loads for the sake of convenience, and their relationships with the sea states actually encountered by the ship are ambiguous. For this reason, it is difficult to offer these design loads to designers and ship operators for use as design conditions and operating conditions, and to establish clear-cut relationships between these conditions. In view of this background, various efforts, for example, by many researchers (Toki (1997), Kawabe (1999), ClassNK (1999), and Baarholm & Moan (2000)) have been made in recent years for developing estimation methods of the design sea states in a rational manner. However, these methods cannot be considered practical. Under these circumstances, the authors developed practical methods for estimating design sea states for primary structural members of tankers (Shigemi & Zhu, 2003), bulk carriers (Zhu & Shigemi, 2003), and container ships focusing mainly on yielding and buckling strengths for which the maximum loads are critical. These methods are detailed in this paper. The authors have also developed practical methods for estimating design regular waves and design loads corresponding to the design sea states, which are also described in this paper.

* Research Institute

The design sea states, design regular waves and design loads used in this paper are defined as follows:

Design sea state: Short-term sea state that generates response values equivalent to the long-term predictions of stress (North Atlantic Ocean, whole year, exceedance probability $Q=10^{-8}$, all headings) for primary structural members of the ship.

Design regular wave: Regular wave that generates response values equivalent to the response values generated in irregular waves under design sea state.

Design loads: Loads acting on the hull structure under design regular waves.

The work, the results of which are detailed in this paper, has been done in five stages, which may be summarized as follows.

1) Stress response functions are determined for primary structural members of a double-hull VLCC, a Cape-size bulk carrier, and a post-Panamax container ship using the most advanced structural analysis method currently available. The combinations of mean wave period and wave encountering angle when the standard deviation per significant wave height becomes maximum are evaluated by using the results of short-term predictions, and the dominant short-term sea states for strength of primary structural members are selected.
2) The dominant load components that reproduce short-term sea states equivalent to the selected short-term sea states at stress level are identified. Using these identified dominant load components, the significant wave heights and maximum wave heights that generate responses equivalent to the long-term predictions of the stresses are evaluated. Here, the long-term prediction is made by the widely used long-term prediction methods proposed, e.g., by Fukuda (1967).
3) Based on the results of stages 1) and 2), the short-term sea states that generate the response values equivalent to the long-term predictions of the stresses acting on primary structural members of tankers, bulk carriers, and container ships are proposed as design sea states. Practical methods for estimating the design sea states using simplified formulae are also proposed based on the results of series calculations.
4) For further practical use from the design viewpoint, regular waves that generate response values equivalent to the response values under design sea states are proposed as design regular waves, considering that the regular waves are simple and the phases between various design loads are clear. Various loads that act on the hull structure in the design regular waves are also proposed as design loads. Furthermore, practical methods for estimating the design regular waves and design loads using simplified formulae are proposed based on the results of series calculations.
5) The design loads obtained by the simplified formulae proposed here are applied to the hold models of a double-hull VLCC, a Cape-size bulk carrier, and a post-Panamax container ship. The resulting stresses are then compared with the long-term predictions of stresses, and the validity of the simplified formulae is verified.

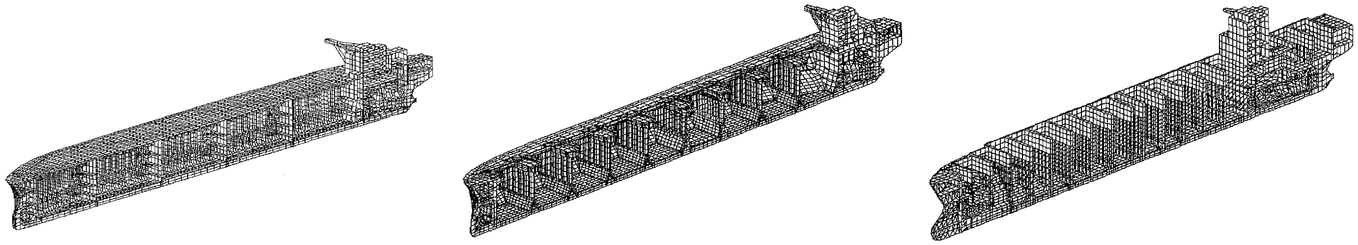
2. Design Sea State

2.1 Mean Wave Period and Wave Encountering Angle

Making use of the statistical property that only the sea state at which the maximum response, that is, the standard deviation of the response value becomes maximum, is significant for the long-term predicted value in the range of small exceedance probability (where the extreme value may occur just once or several times in the intended service life of a ship) (Mano, 1972), the selection of the mean wave period and wave encountering angle required for setting the design sea state is studied.

Short-term predictions of stress were calculated for a double- hull VLCC ($L \times B \times D \times d = 320$ m $\times$ 60 m $\times$ 29 m $\times$ 20 m), a Cape-size bulk carrier ($L \times B \times D \times d = 280$ m $\times$ 45 m $\times$ 24 m $\times$ 18 m), and a post-Panamax container ship ($L \times B \times D \times d = 287$ m $\times$ 40 m $\times$ 24 m $\times$ 13 m) using the FE models shown in Figure 1, respectively. Representative structural members considered to be severely stressed from the viewpoint of structural strength were selected from each hold of each ship. Figure 2 shows examples of them. The stress components selected for plate members included normal stress (σ_x, σ_y) in the longitudinal, transverse and vertical directions and shear stress (τ_{xy}) components that are considered to be dominant on the strength of each member examined. Axial stresses (σ_a) were selected for face plates. Short-term predictions of 254 stresses each for the tanker and bulk carrier, and 150 stresses for the container ship were made for each load condition.

Table 1 shows the analysis conditions used for calculating stress response functions and short-term predictions. Full load condition, partial load condition, and ballast condition were chosen in the calculations for the tanker and container ship respectively, while homogenous load condition, alternate load condition, normal ballast condition, and heavy ballast condition were chosen for the bulk carrier. The design speed of each ship was used in the wave load analyses. ISSC-1964 wave spectrum and directionality function ($(2/\pi)\cos^2\theta$ (θ is the relative angle between ship heading and the mean direction of propagation of the wave system)) were used in short-term predictions. To consider the effect of the nonlinearity of hydrodynamic pressure near the waterline due to wave height in the structural analysis, stress response functions were determined using the time history analysis of one wave period divided into twelve equal parts.

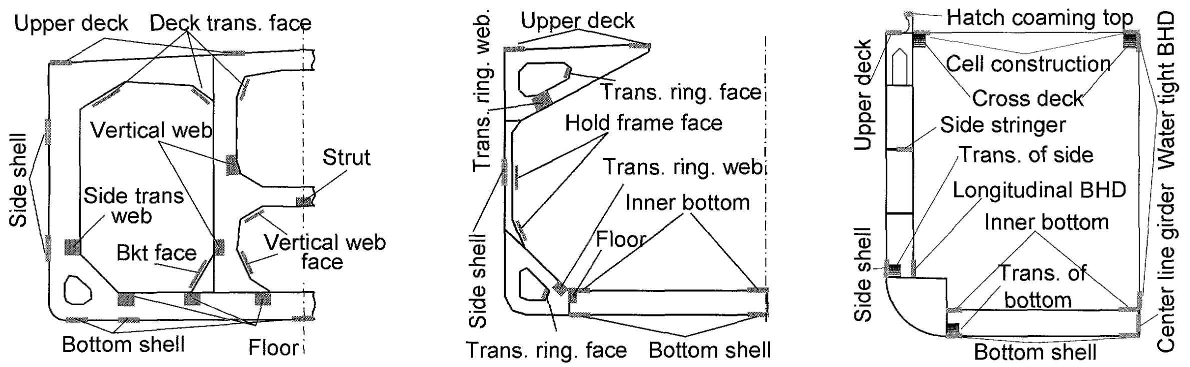


(a) Double-hull VLCC model (b) Cape-size bulk carrier model (c) Post-Panamax container ship

Fig.1 FE models used for direct structural analysis.

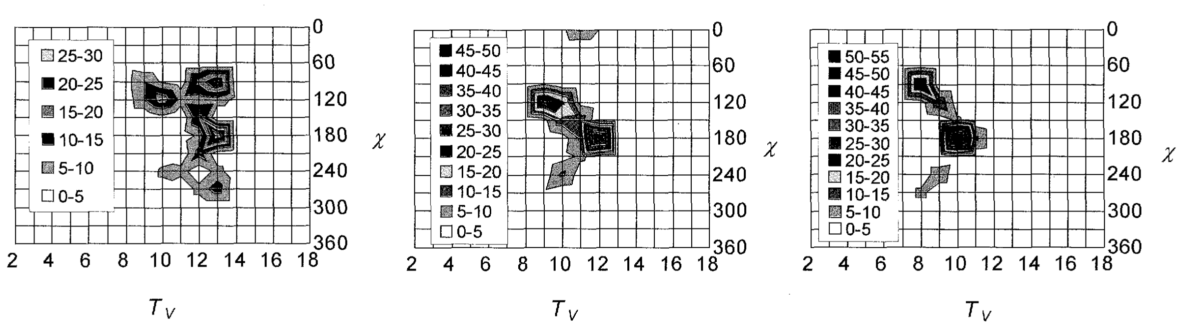
Table 1 Analysis Conditions

Load condition	*Tanker and container ship*	***Full load condition***		***Partial load condition***	***Normal ballast condition***
	Bulk carrier	***Homogenous load condition***	***Alternate load condition***	***Normal ballast condition***	***Heavy ballast condition***
Wave height (H)		***H = 5.0 m***			
Wavelength (λ/L_{pp})		***λ/L_{pp} = 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.7, 2.0, 2.3***			
Wave encountering angle (χ)		***χ = 0, 30, 60, 90, 120, 150, 180, 210, 240, 270, 300, 330 deg.***			



(a) Double-hull VLCC (b) Cape-size bulk carrier (c) Post-Panamax container ship

Fig. 2 Examples of locations where stresses of critical structural members are examined.



(a) for double-hull VLCC (b) for Cape-size bulk carrier (c) for post-Panamax container

Fig. 3 Dominant sea states in terms of mean wave period and wave encountering angle.

Fig. 3 shows the distributions of dominant sea states set for various stress components, taking the full load condition of each ship as representative examples. The numbers in the figure represent the total number of locations examined, where the mean wave period (T_V) and the wave encountering angle (χ) at which the standard deviation per significant height becomes maximum coincide. The larger this total number, the more dominant are the effects of the mean wave period and the wave encountering angle on hull structural strength. In the example of the tanker, the dominant short-term sea states are concentrated at T_V=13 s, χ=180° (head sea), T_V=13 s, χ=90° (beam sea), and T_V=10 s, χ=120° (oblique sea). In the example of the bulk carrier, they are concentrated at T_V=12 s, χ=180° (head sea), T_V=11 s, χ=0° (following sea), and T_V=9 s, χ=120° (oblique sea). In the example of the container ship, they are concentrated at T_V=10 s, χ=180° (head sea), T_V=8 s, χ=90° (beam sea) and T_V=9 s, χ=120° (oblique sea).

The above results and those of other load conditions investigated show that the design sea states set for each load condition for the primary structural members examined can be represented by a few specific short-term sea states.

To accurately determine the structural response in irregular waves, the stress response functions should be determined by performing structural analysis beforehand for all combinations of wavelength and wave encountering angles in regular waves. This seems to be impractical from a design point of view. On the other hand, if the correlation between design sea states strictly selected using stress response functions and those selected using wave-induced load response functions can be confirmed, then the design sea states can be set more easily by wave-induced load response functions instead of stress response functions.

Accordingly, the wave-induced load components considered to be dominant on the stresses in structural members are identified from the load components (ship motions, accelerations, hydrodynamic pressures, wave-induced sectional forces, and moments). Further, the dominant load components that could reproduce short-term sea states equivalent to the short-term sea states selected at the stress level are proposed, as indicated below (Shigemi & Zhu, 2003).

(1) Vertical bending moment (head sea)
(2) Vertical bending moment (following sea)
(3) Roll
(4) Hydrodynamic pressure at waterline

By using the dominant load components (1) to (4), the mean wave period and wave encountering angle of the design sea states can be easily determined as those at which the standard deviation per significant wave height of each dominant load component becomes maximum.

2.2 Significant Wave Height

Significant wave height (H_W) for generating the long-term prediction (a) (exceedance probability Q=10^{-8}, all headings) of various load responses as 1/1000 times the maximum expected value is given by the formula below. IACS wave data (IACS, 2000) is used for long-term predictions.

$$H_W = \frac{a(Q=10^{-8})}{2\times[R_{LOAD}/H_W(T_V,\chi)]_{\max}\times 1.9}\ \text{(m)} \qquad (1)$$

Here, $[R_{LOAD}/H_W(T_V,\chi)]_{\max}$ is the maximum value of standard deviation per significant wave height determined from the response function of load component, 2 is the constant for determining the significant value of extreme value in irregular response from the standard deviation, and 1.9 is the constant for determining the maximum response value of 1,000 waves from the significant value.

The results of significant wave height obtained by *Eq.* (1) for each of the load conditions corresponding to vertical bending moment (M_y), hydrodynamic pressure at the waterline (P_{WL}), and rolling motion (*Roll*) are shown in Figure 4. The horizontal axis indicates the wavelength of regular waves at which the response function of each load component becomes maximum, while the vertical axis indicates the significant wave height. The notations "*T-full*", "*T-part*" and "*T-nbal*" in Figure 4 indicate the results of the full load, partial load, and normal ballast conditions corresponding to series calculations for 27 tankers. The notations "*B-fhom*", "*B-falt*", "*B-nbal*", "*B-hbal*", and "*B-part*" are the results of the homogenous load, alternate load, normal ballast, heavy ballast, and partial load condition, respectively, for series calculations on 22 bulk carries. In addition, the notations "*C-full*", "*C-part*", and "*C-nbal*" indicate the results of the full load, partial load, and normal ballast condition corresponding to series calculations on 18 container ships.

Although some variation can be observed in the short wavelength region in Figure 4, it can be concluded that the significant wave height bears a strong relationship with the wavelengths of regular waves when the load response function becomes maximum regardless of the type of ship, type of load components, ship length, or load conditions. Consequently, the significant wave height can be set by determining the wavelength when the response function of each dominant load component becomes maximum and by "fitting" the [wavelength of regular waves] – [significant wave height] relationship.

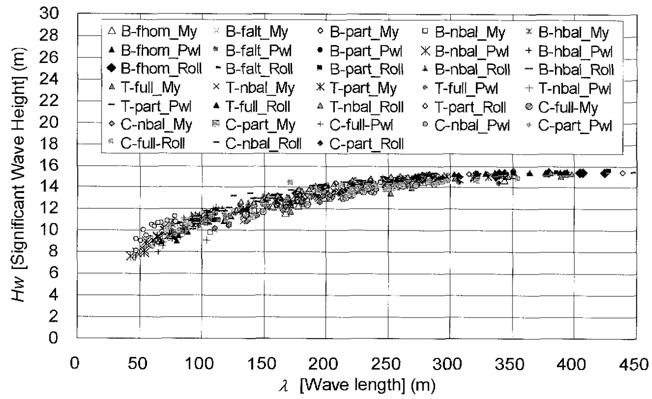


Fig. 4 Significant wave heights in short-term sea states resulting in same level of response as long-term prediction at 10^{-8} (relation between wavelength and significant wave height).

2.3 Proposal for Design Sea States

Based on the evaluations given in Sections 2.1 and 2.2, the short-term sea states set for the dominant load components (1) to (4) are proposed as design sea states, assigned the notations given below for identification, and used.

Short-term sea state set according to (1): Design sea state *L-180*
Short-term sea state set according to (2): Design sea state *L-0*
Short-term sea state set according to (3): Design sea state *R*
Short-term sea state set according to (4): Design sea state *P*

The design sea state *L-180* is a short-term sea state in which the acceleration in the vertical direction due to the combination of pitching and heaving motions, and the vertical bending moment generally become maximum. The design sea state *L-0* is a short-term sea state almost similar to the design sea state *L-180*, but the acceleration in the vertical direction becomes minimum. The design sea state *R* is a short-term sea state in which the transverse acceleration due to rolling motion and the hydrodynamic pressure having asymmetric distribution generally become maximum. The design sea state *P* is a short-term sea state in which the hydrodynamic pressure at the waterline of the weather side and the acceleration in the vertical direction due to heaving motion generally become maximum.

Furthermore, practical methods for setting the design sea state, such as wave encountering angle, mean wave period and significant wave height, are proposed as shown in Table 2 based on the results of the series calculations for tankers, bulk carriers, and container ships performed on dominant load components using the strip method. A total of 27 tankers, 22 bulk carriers and 18 container ships were used for the series calculations.

Tables 3–5 show the wave encountering angles for dominant load components when the standard deviation per significant wave height becomes maximum for tankers, bulk carriers and container ships. M_y, Roll, and P_{WL} in the tables indicate the results for vertical bending moment amidships, rolling motion, and hydrodynamic pressure at the waterline, respectively. From Tables 3–5, it is observed that the wave encountering angle when the standard deviation per significant height becomes maximum remains constant as given below, regardless of the type of the ship and length of the ship.

Design sea state L-180: 180° (head sea)
Design sea state L-0: 0° (following sea)
Design sea state R: 90° or 60° (beam or quartering sea)
Design sea state P: 90° (beam sea)

Although the wave encountering angle determined for vertical bending moment in the full load condition in Table 3 and Table 4 cannot be specifically identified as 180 or 0 degrees, it can be covered by considering both *L-180* and *L-0* as the design sea states.

Moreover, it is observed in the cases of tankers and bulk carriers that there are some differences between the short-term sea state *P* (beam sea, χ=90°) selected based on the response functions of wave-induced loads and the short-term sea state *P* (oblique sea, χ=120°) selected from the stress response functions in the homogenous load condition in Section 2.1.

Table 2 Design Sea States

Design condition	Wave encountering angle (χ_j)	Mean wave period (T_{Vj})	Maximum wave height (H_{maxj})
L-180	Head sea (180 *deg.*)	$T_{Vj}=0.85\{(2\pi\lambda_j)/g\}^{1/2}$ (*s*)	$H_{maxj} = 1.9H_{Wj}$ (*m*) H_{Wj} : Significant wave height, calculated as below $H_{Wj} = C_1 C_{2j}$ (*m*) $C_1 = 10.75\text{-}\{(300\text{-}L)/100\}^{1.5}$ $L \le 300$ m $C_1 = 10.75$ 300 m $< L \le$ 350 m $C_1 = 10.75\text{-}\{(L\text{-}350)/150\}^{1.5}$ 350 m $< L$ $C_{2j} = \{(L+\lambda_j\text{-}25)/L\}^{1/2}$ L: Scantling length of ship, in meters
L-0	Following sea (0 *deg.*)	*j*: L-180, L-0, R, P λ_j: Wavelength of design regular wave corresponding to each design sea state, in meters	
R	χ_R (see Table 6)		
P	Beam sea (90 *deg.*)		

However, the short-term prediction is comparatively insensitive to the wave encountering angle and the mean wave period, and the difference is small; therefore, the effect due to this difference is considered to be small. Meanwhile, with a reduction in draft, as in the partial load condition and ballast condition, the short-term sea state selected by the stress response functions also approaches 90° from 120°.

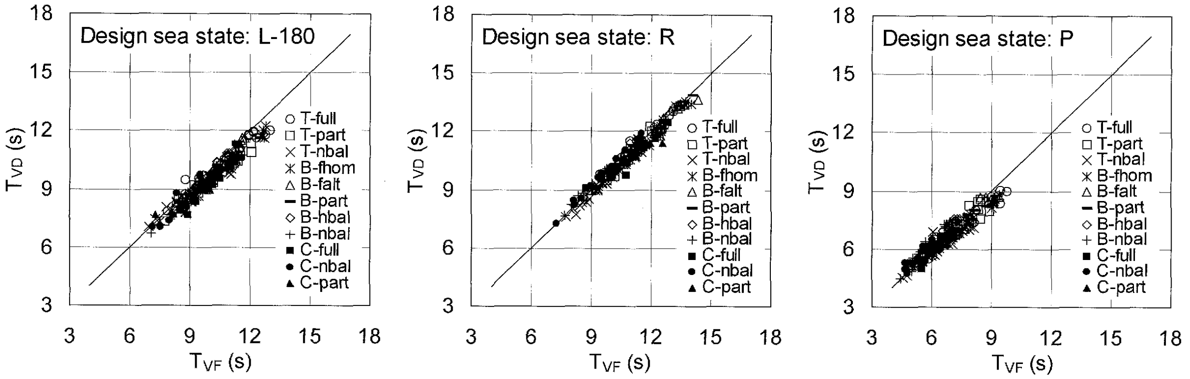
Figures 5 and 6 show comparisons between the mean wave periods (T_{VD}) and significant wave heights (H_{WD}) determined directly from short-term predictions and those (T_{VF} and H_{WF}) determined by the simplified formulae shown in Table 2, corresponding to the design sea states *L-180*, *R* and *P* for tankers, bulk carriers, and container ships, respectively. It is concluded from Figures 5 and 6 that the mean wave period and significant wave height can be estimated with adequate accuracy using the simplified formulae proposed in Table 2.

Table 3 Wave Encountering Angles when Standard Deviations of Dominant Wave-Induced Loads Become Maximum for Tankers

Dominant wave-induced loads		M_y			Roll			P_{WL}		
Number	L_{PP} (m)	full	nbal	part	full	nbal	part	full	nbal	part
1	110	180	180	-	90	90	-	90	90	-
2	130	180	180	-	90	90	-	90	90	-
3	143	180	180	-	90	90	-	90	90	-
4	145	180	180	180	90	90	90	90	90	90
5	160	0	180	180	90	90	90	90	90	90
6	165	180	180	180	90	90	90	90	90	90
7	170	180	180	180	90	90	90	90	90	90
8	172	180	180	180	90	90	90	90	90	90
9	180	180	180	-	90	90	-	90	90	-
10	194	0	180	180	90	90	90	90	90	90
11	200	0	180	180	90	90	90	90	90	90
12	210	180	180	180	90	90	90	90	90	90
13	215	180	180	180	90	90	90	90	90	90
14	220	180	180	180	90	90	90	90	90	90
15	220	180	180	180	90	90	90	90	90	90
16	230	180	180	180	90	90	90	90	90	90
17	230	180	180	180	90	90	90	90	90	90
18	235	0	180	180	90	90	90	90	90	90
19	235	180	180	180	90	90	90	90	90	90
20	260	180	180	180	90	90	90	90	90	90
21	305	0	180	180	90	90	90	90	90	90
22	310	0	180	180	90	90	90	90	90	90
23	315	0	180	180	90	90	90	90	90	90
24	318	0	180	180	90	90	90	90	90	90
25	320	180	180	180	90	90	90	90	90	90
26	320	180	180	180	90	90	90	90	90	90
27	323	180	180	180	90	90	90	90	90	90

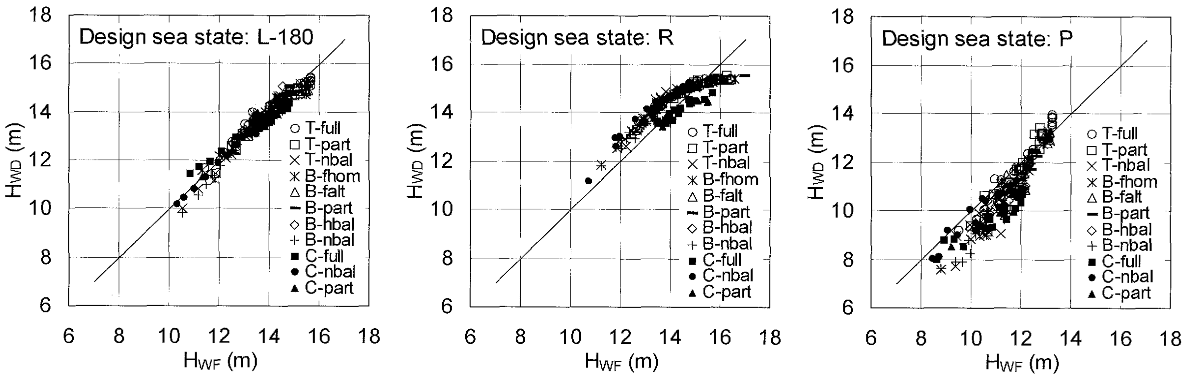
Table 4 Wave Encountering Angles When Standard Deviations of Dominant Wave-induced Loads Become Maximum for Bulk Carriers

Dominant wave-induced loads		M_y					Roll					P_{WL}				
Number	L_{PP} (m)	full	falt	nbal	hbal	part	full	falt	nbal	hbal	part	full	falt	nbal	hbal	part
1	107	180	-	180	-	-	90	-	90	-	-	90	-	90	-	-
2	127	180	-	180	-	-	90	-	90	-	-	90	-	90	-	-
3	138	180	-	180	-	-	90	-	90	-	-	90	-	90	-	-
4	148	180	-	180	-	-	90	-	90	-	-	90	-	90	-	-
5	150	180	-	180	-	-	90	-	90	-	-	90	-	90	-	-
6	160	180	-	180	-	180	90	-	90	-	90	90	-	90	-	90
7	172	180	0	180	180	-	90	90	90	90	-	90	90	90	90	-
8	174	180	0	180	180	-	90	90	90	90	-	90	90	90	90	-
9	177	180	-	180	180	-	90	-	90	90	-	90	-	90	90	-
10	181	180	0	180	180	-	90	90	90	90	-	90	90	90	90	-
11	182	180	0	180	180	-	90	90	90	90	-	90	90	90	90	-
12	215	180	0	180	180	180	90	90	90	90	90	90	90	90	90	90
13	217	180	-	180	180	-	90	-	90	90	-	90	-	90	90	-
14	217	180	0	180	-	-	90	90	90	-	-	90	90	90	-	-
15	225	180	-	180	180	180	90	-	90	90	90	90	-	90	90	90
16	230	180	-	180	180	180	90	-	90	90	90	90	-	90	90	90
17	260	0	0	180	180	180	90	90	90	90	90	90	90	90	90	90
18	278	180	0	180	180	180	90	90	90	90	90	90	90	90	90	90
19	278	180	0	180	180	180	90	90	90	90	90	90	90	90	90	90
20	280	180	0	180	180	180	90	90	90	90	90	90	90	90	90	90
21	285	0	0	180	0	-	90	90	90	90	-	90	90	90	90	-
22	285	180	0	180	180	180	90	90	90	90	90	90	90	90	90	90



(a) L-180 (vertical bending moment) (b) R (rolling motion) (c) P (hydrodynamic pressure)

Fig. 5 Comparisons of mean wave periods obtained by direct load analyses and those obtained by simplified formulae for tankers, bulk carriers, and container ships.



(a) L-180 (vertical bending moment) (b) R (rolling motion) (c) P (hydrodynamic pressure)

Fig. 6 Comparisons of significant wave heights obtained by direct load analyses and those obtained by simplified formulae for tankers, bulk carriers, and container ships.

Table 5 Wave Encountering Angles When Standard Deviations of Dominant Wave-induced Loads Become Maximum for Container Ships

Dominant wave-induced loads		M_y			Roll			P_{WL}		
Number	L_{PP} (m)	full	nbal	part	full	nbal	part	full	nbal	part
1	110	180	-	180	60	-	90	90	-	90
2	121	180	-	180	60	-	90	90	-	90
3	136	180	180	180	60	60	90	90	90	90
4	150	180	-	180	60	-	90	90	-	90
5	172	180	-	180	60	-	90	90	-	90
6	181	180	-	180	60	-	90	90	-	90
7	191	180	-	-	60	-	-	90	-	-
8	195	180	-	180	60	-	90	90	-	90
9	202	180	-	180	60	-	90	90	-	90
10	230	180	180	180	60	60	90	90	90	90
11	230	180	-	180	60	-	90	90	-	90
12	236	180	180	180	60	60	90	90	90	90
13	261	180	180	180	60	60	90	90	90	90
14	273	180	-	180	60	-	90	90	-	90
15	281	180	-	180	60	-	90	90	-	90
16	283	180	180	180	60	60	90	90	90	90
17	283	180	-	180	60	-	90	90	-	90
18	287	180	180	180	60	60	90	90	90	90

3. Design Regular Waves

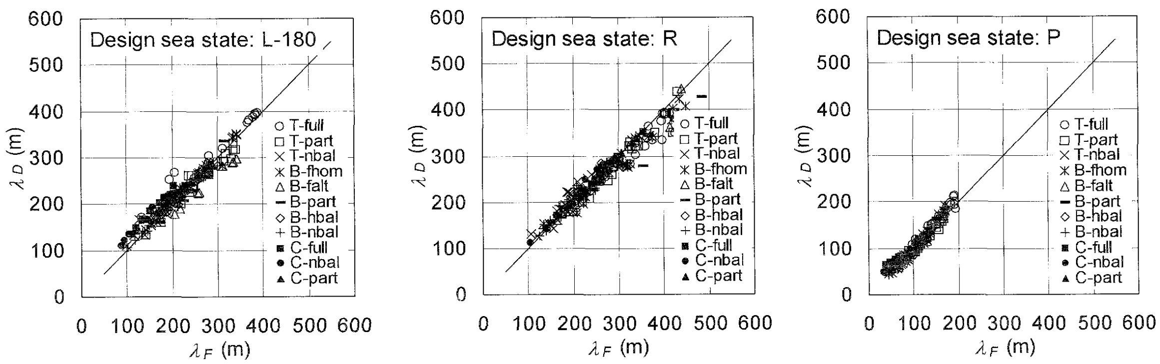
To evaluate hull structural strength under design sea states, however, either short-term predictions need to be made using wave spectra after determining the response functions of stresses, or simulation in irregular waves must be carried out. However, both methods are presently impractical from the design point of view. In view of the above, design loads are proposed based on design regular waves for dominant load components in this section. The design regular waves proposed here are regular waves that generate response values equivalent to the response values generated in irregular waves under the design sea states proposed in Section 2.

Table 6 gives a summary of practical methods for setting design regular waves using simplified formulae for tankers, bulk carriers, and container ships developed based on the results of series calculations for each respective ship type performed on the dominant load components using the strip method.

Figure 7 shows comparisons of the wavelengths (λ_F) determined using the simplified formulae listed in Table 6 and those (λ_D) determined by direct load analyses using the strip method for 27 tankers, 22 bulk carriers, and 18 container ships. From Figure 7, it is concluded that the simplified formulae for the wavelengths of the design regular waves are adequately accurate.

In Table 6, C_4 is taken as the coefficient for correcting the response value in irregular waves to the response value in regular waves considering the configuration of the response function in regular waves and the wave spectrum of the irregular waves. Figure 8 shows the results of C_4 of the series calculations corresponding to the design sea states *L-180*, R and P for tankers, bulk carriers, and container ship. As the configuration of the response function and the wave spectrum for the same load component are similar, the value of C_4 remains practically constant, as shown in Figure 8, regardless of the type of ship, load conditions and length of the ship. The bold lines in the figure indicate the mean value of C_4, which have been proposed for each dominant load component, as shown in Table 6.

In Table 6, C_5 is taken as the correction coefficient considering the three-dimensional effects and nonlinear effects due to wave height in large waves. Based on the results of model tests (Zhu et al, 2002; Miyake and Zhu, 2004) and analysis using the Rankine source method (Miyake and Zhu, 2001), the values of the correction coefficient C_5 are proposed. Figure 9 shows an example of the model test results of a blunt ship in large waves. This figure shows the results of short-term predictions of rolling motion in a beam sea (χ=90°) obtained by the measured data. "H=6 m", "H=10 m" and "H=12 m" in the figure indicate the model test results corresponding to the wave heights of 6 m, 10 m and 12 m, respectively. "Strip method" indicates the results calculated using the strip method. From the figure, it can be seen that the model test results corresponding to a 6 m wave height agree well with the results obtained by the strip method. However, the maximum value of short-term prediction decreases as the wave height increases from 6 m to 12 m, due to nonlinear phenomena.



(a) L-180 (vertical bending moment) (b) R (rolling motion) (c) P (hydrodynamic pressure)

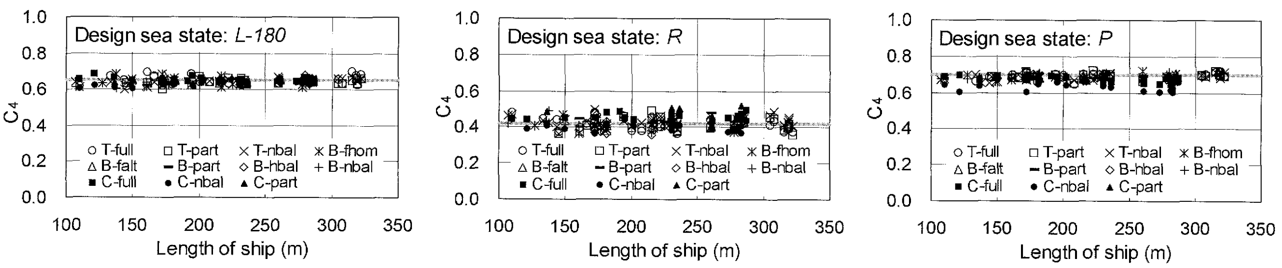
Fig. 7 Comparisons of wavelengths of design regular waves obtained by direct load analyses and those obtained by simplified formulae for tankers, bulk carriers, and container ships.

Table 6 Design Regular Waves

Design conditions	Wave encountering angle (χ_j)	Wavelength (λ_j)	Regular wave height (H_j)	C_4	C_5
L-180	180 (*deg*)	$\lambda_{L\text{-}180} = C_{L1}(1+d_i/d_f)L$ (*m*)	$H_j = C_4 \cdot C_5 \cdot H_{\max j}$ (m) C_4 : Correction coefficient for regular wave height C_5 : Correction coefficient for 3D and non-linear effects	0.65	0.9
L-0	0 (*deg*)	$\lambda_{L\text{-}0} = C_{L1}\{1+(2d_i)/(3d_f)\}L$ (*m*)			
R	χ_R	$\lambda_R = g/(2\pi)T_E^{\;2}$ (*m*)		0.42	0.8
P	90 (*deg*)	$\lambda_P = \{0.2+(C_{L2}d_i)/d_f\}L$ (*m*)		0.70	0.7

Where:
C_{L1}=0.6, C_{L2}=0.4 for tankers and bulk carriers
C_{L1}=0.5, C_{L2}=0.15 for container ships
$T_E = T_R$ (s), λ_R= 90 (deg) for tankers and bulk carriers
$T_E = 0.5\{T_R + (T_R^2 - 2\pi V T_R / g)^{1/2}\}$ (s), χ_R= 60 (deg), when $T_R > 2\pi V/g$; $T_E = T_R$ (s), χ_R= 90 (deg), when $T_R \leq 2\pi V/g$ for container ships

Notes:
χ_R : wave encountering angle for design condition R, in degrees
T_E : wave encountering period, in seconds
T_R : natural period of roll motion, in seconds
V : design speed of ship, in knots
d_f : design moulded draft of ship, in meters
d_i : draft amidships for the relevant load condition, in meters
H_j : wave height of design regular wave corresponding to each design sea state, in meters
H_{maxj} : maximum wave height corresponding to each design sea state, in meters
L : scantling length of ship, in meters
λ_j : wavelength of design regular wave corresponding to each design sea state, in meters



(a) L-180 (vertical bending moment) (b) R (rolling motion) (c) P (hydrodynamic pressure)

Fig. 8 Coefficient C_4 corresponding to the design regular waves determined by each dominant load.

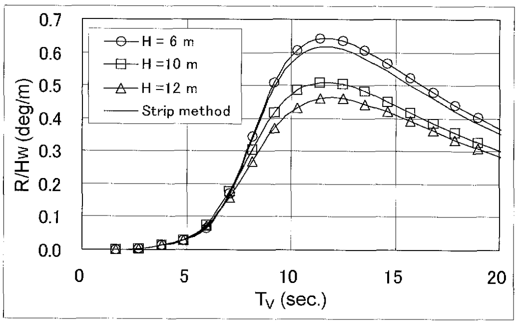


Fig. 9 Standard deviations of rolling motion in waves of different wave heights obtained by model tests and numerical calculation.

4. Design Loads

Practical methods for setting design loads using simplified formulae are briefly introduced in this Section. Although a detailed discussion of the simplified formulae and their background is omitted here due to limitations in space, the following design loads have been developed based on the results obtained by series calculations on the tankers, bulk carriers, and container ships using the strip method in design regular waves mentioned in Section 3. Details of the proposed simplified formulae can be found in the respective Guidelines (ClassNK, 2001, 2002, and 2003) listed in the References section of this paper.

(1) Ship motions (pitching, rolling)
(2) Accelerations at the center of gravity of ship (vertical and transverse directions)
(3) Accelerations at the center of gravity of tank or hold (vertical and transverse directions)
(4) Hydrodynamic pressures
(5) Hull girder moments (horizontal bending moment)
(6) Superimposition ratio of hull girder stresses

Figure 10 gives a comparison of the long-term values of pitching motion, rolling motion, and vertical acceleration at the center of gravity of the ship due to heaving motion for the full load condition corresponding to tankers, bulk carriers, and container ships obtained by direct load analyses ($Pitch_D$, $Roll_D$, A_{HeaveD}) and the values obtained by the simplified formulae ($Pitch_F$, $Roll_F$, A_{HeaveF}) as some examples of ship motions and acceleration. Three-dimensional effects and nonlinear effects in large waves are not considered in the long-term predictions. Therefore, the correction coefficient C_5 shown in Table 6 has not been used in the simplified formulae. (Hereinafter, the same assumption is made for the comparison with long-term values). Although there are slight differences in the results using the simplified formulae, Figure 10 shows that the simplified formulae are quite accurate for practical use.

Figure 11 shows comparisons of the hydrodynamic pressure distributions at the midship cross section obtained by the simplified formulae and those obtained based on the long-term prediction for the full load condition corresponding to the double-hull VLCC, Cape-size bulk carrier, and post-Panamax container ship, respectively. In each figure, the left side of the section is the weather side, while the right side is the lee side.

From Figure 11, it is observed that the hydrodynamic pressure (P_P) corresponding to the design regular waves *P* is almost equal to the long-term prediction value from the waterline to the bilge keel, the hydrodynamic pressure (P_R) corresponding to the design regular waves R is almost equal to the long-term prediction value around the bilge keel, and the hydrodynamic pressure (P_L) corresponding to design regular waves *L-180* and *L-0* is almost equal to the long-term prediction value near the bottom centerline. That is, the maximum values for the hydrodynamic pressures P_P, P_R, and P_L found using the simplified formulae are seen to be almost equivalent to the long-term prediction value for hydrodynamic pressure.

Furthermore, as an example, the distributions of the external and internal dynamic pressures obtained by the proposed simplified formulae corresponding to the four kinds of design regular waves are shown in Figure 12 for the double-hull VLCC for reference.

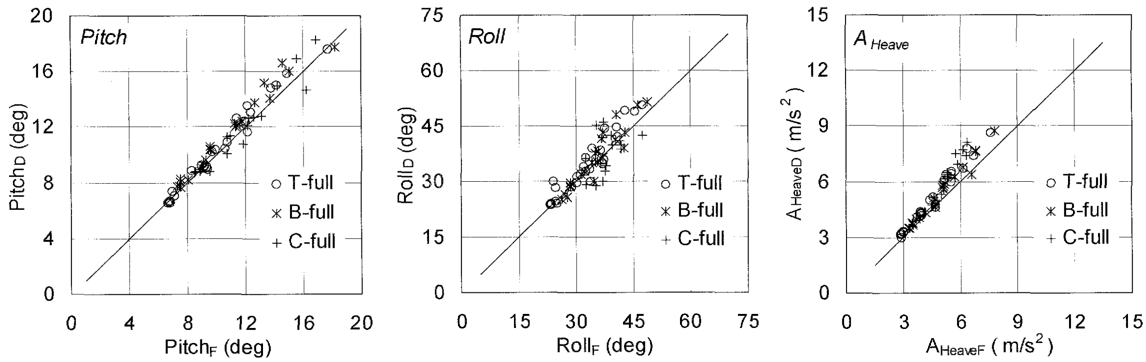


Fig. 10 Comparisons of the pitch, roll and acceleration at the center of gravity of a ship due to heave obtained by direct load analyses and those obtained by the simplified formulae for the full load condition.

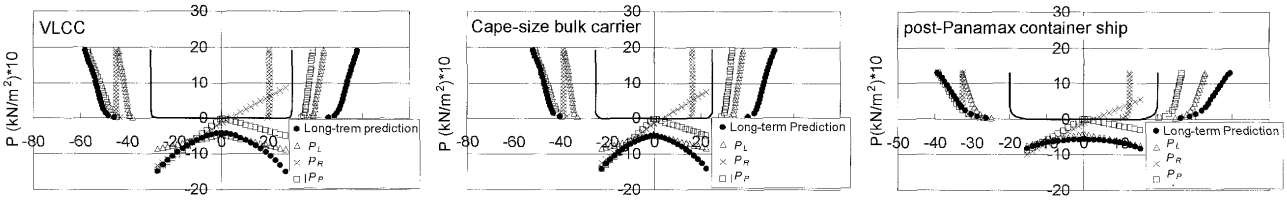
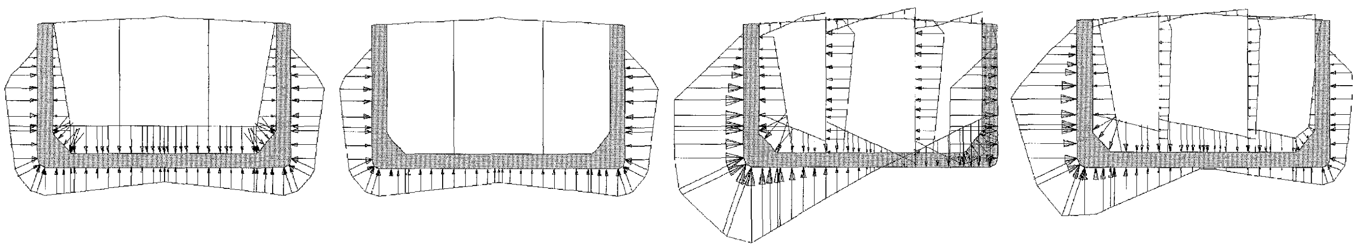


Fig. 11 Comparisons of the pressure distributions obtained by long-term prediction and those obtained by the simplified formulae for full load condition corresponding to a double-hull VLCC, Cape-size bulk carrier, and post-Panamax container ship.



(a) L-180 (head sea) (b) L-0 (following sea) (c) R (beam sea) (d) P (beam sea)

Fig. 12 Four different kinds of design loads (external and internal dynamic pressures) in regular design waves for a double-hull VLCC.

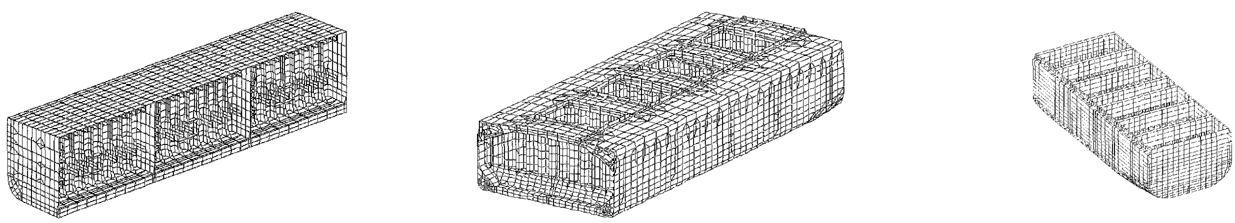
5. Verification of Design Loads by Structural Analysis

5.1 Method of Verification

The accuracy of the simplified formulae is verified by comparing the stresses obtained by direct structural analysis applying the design loads obtained by the proposed simplified formulae with the long-term predictions of stress for the double-hull VLCC, Cape-size bulk carrier, and post-Panamax container ship referred to in Section 2.1.

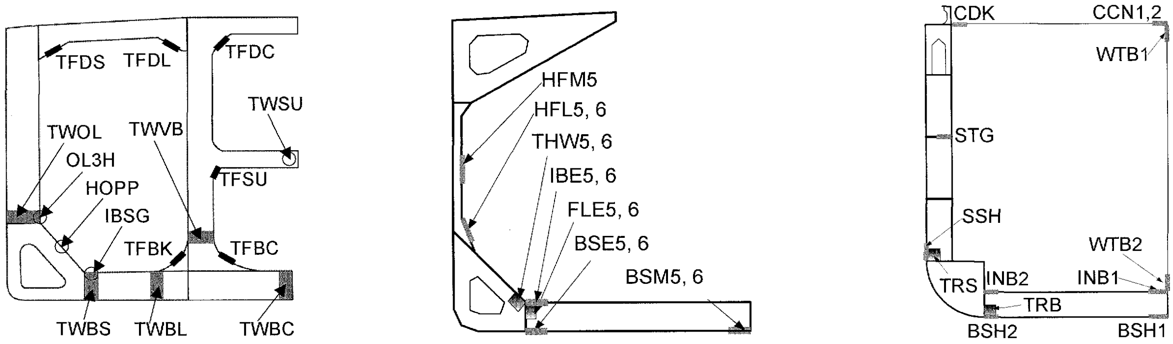
The stress determined by the simplified formulae is the stress per wave height obtained by loading the hold model shown in Figure 13 with the difference in the design loads corresponding to the wave crest and trough (or weather side down and up) determined by the simplified formulae multiplied by the design wave height determined by the simplified formulae. The long-term prediction of stress is determined directly using the stress response function of the entire ship model shown in Figure 1. For estimating the long-term predictions, the ISSC-1964 wave spectra (directional distribution: $\cos^2\theta$), the IACS wave data, and the probability level of 10^{-8} were used.

The compared members for the tanker were the primary structural members at the midship section (No. 3 C.O.T.) shown in Figure 14(a). The compared members for the bulk carrier were the primary structural members at the midship section between Nos. 5 and 6 holds shown in Figure 14(b). Furthermore, the compared members for the container ship were the primary structural members at the midship section between Nos. 5 and 6 holds shown in Figure 14(c). For the Cape-size bulk carrier, the No. 5 hold is a cargo hold and the No. 6 hold is an empty hold in alternate load condition. The stress components used for comparison were axial stresses (σ_a), shear stresses (σ_{xy}), and normal stresses (σ_y) in the transverse or vertical direction of the ship, and each of these stresses were identified by affixing the notations "a", "*xy*" and "*y*", respectively.



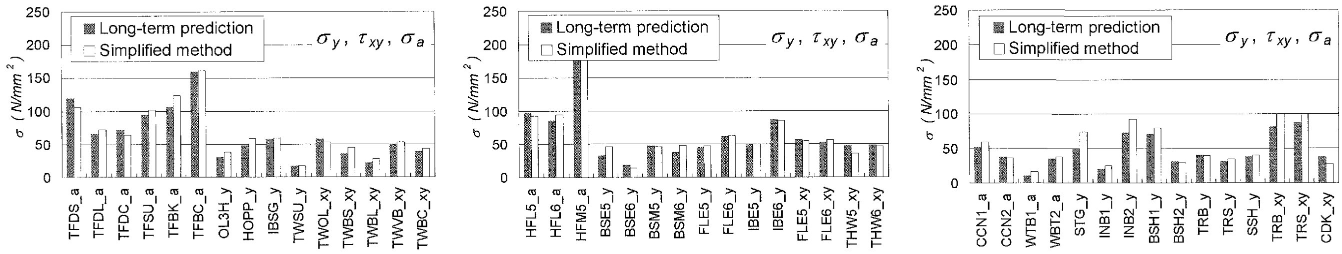
(a) Double-hull VLCC (b) Cape-size bulk carrier (c) Post-Panamax container ship

Fig. 13 Hold FE models used for structural analysis under design loads determined using simplified formulae.



(a) Double-hull VLCC (b) Cape-size bulk carrier (c) Post-Panamax container ship

Fig. 14 Locations of the primary structural members used in the comparative study.



(a) Tanker (full load condition) (b) Bulk carrier (alternate load condition) (c) Container ship (full load condition)

Fig. 15 Comparisons of the stresses obtained by long term prediction and those obtained by the simplified formulae.

5.2 Verification Results of the Design Loads

Figure 15 shows comparisons of the maximum stress values among the four cases of design regular waves obtained by the simplified formulae and the long-term predictions for the full load condition. It can be concluded from Figure 15 that the maximum values determined using the simplified formulae generally reproduce the long-term predictions to a fairly good level of accuracy. At some of the locations, the stresses by the simplified formulae exceed or underestimate the long-term predictions by about 20 to 30%. Even at these locations, the maximum values as shown in Figure 15 are comparatively small, and their maximum difference is only about 20 N/mm^2. Therefore, their effect on strength assessment is considered to be small.

6. CONCLUSION

Considering the strength of primary structural members, dominant short-term sea states, which generate response values equivalent to long-term predictions of stress at the probability level $Q=10^{-8}$, were evaluated and proposed as design sea states, and practical methods for setting the design sea states were proposed using the results of series calculations.

In addition, regular waves that generate response values equivalent to the response values generated in irregular waves have been proposed as design regular waves, and loads acting on the hull structure in the design regular waves were proposed as the design loads. Furthermore, practical methods for setting the design regular waves and design loads were proposed using simplified formulae based on series calculations.

The conclusions drawn from the study described in this paper can be summarized as follows:

1) The dominant short-term sea states for primary structural members of tankers, bulk carriers, and container ships can be represented by a few specific short-term sea states. Furthermore, the dominant short-term sea states can be identified with good accuracy using the response functions of the following dominant load components without using stress response functions:

    Vertical bending moment (head sea)
    Vertical bending moment (following sea)
    Roll
    Wave-induced hydrodynamic pressure at waterline.

2) A method was proposed to convert the maximum wave heights in design sea states to wave heights of design regular waves that generate response values equivalent to the response values generated in irregular waves under design sea states. In addition, a correction method considering three dimensional effects and nonlinear effects due to wave height in large waves was proposed.

3) When three-dimensional effects and nonlinear effects due to wave height in large waves are not considered, the proposed simplified formulae of design loads can be used to assign values equivalent to the long-term predictions of corresponding loads.
4) The values for stresses obtained by structural analysis using the proposed design loads under identical conditions were confirmed to be equivalent to the long-term predictions of stresses.

By using the proposed method, design loads can be set easily for obtaining stresses that are equivalent to long-term predictions of stresses, which are otherwise obtained by direct load analyses and large-scale structural analyses for determining stress response functions. That is, by using the proposed method, tedious direct load analyses and structural analyses can be avoided. As the design loads proposed in this paper are universally applicable to tankers, bulk carriers, and container ships regardless of the differences in structural configurations, intended cargoes, and loading conditions, it would be expected that they would assist in rational design for not only conventional ships but also double side skin bulk carriers and novel ships.

Furthermore, combining with studies on yielding, buckling, ultimate and fatigue strengths (Harada, 2001 and Yamamoto, 2001), and studies on the estimation of corrosion and wastage of ships in service (Yamamoto, 1998), practical and rational strength assessment standards for tanker, bulk carrier, and container ship structures have been developed (ClassNK, 2001, 2002, and 2003).

On the other hand, to properly associate design sea states that are used to evaluate structural strength with the most severe actual sea states that are encountered or likely to be encountered by a ship during its lifetime, natural phenomena such as spatial profiles of waves in such severe sea states and their transformations over time, the loads applied on the ship under the effects of such strong nonlinear phenomena, elasto-plastic response of the hull structure by a complete nonlinear approach when such loads are applied, and many similar topics remain to be studied and explained. The authors wish to further their studies into these topics.

Finally, designers need to submit proposals for ship operating conditions from the perspective of structural strength, operators need to clarify the ship operating conditions from the perspective of safe operation, and classification societies need to propose more rational design loads and strength assessment standards considering ship operational effects. It is the authors' firm conviction that the parties concerned will take appropriate steps to enhance the safety and reliability of ship structures from this aspect as well.

ACKNOWLEDGEMENTS

The authors wish to thank Professor Yasumitsu Tomita of Osaka University, Professor Toichi Fukasawa of Kanazawa Institute of Technology, and Professor Hiroshi Kawabe of the National Defense Academy (currently the Maritime Safety Research Institute of Japan) for their valuable comments and support during the course of this study. The authors also wish to express their gratitude to Professor Hideomi Ohtsubo of the University of Tokyo, Chairman of the Hull Structure Committee of Nippon Kaiji Kyokai (ClassNK), and other participating companies. Furthermore, the authors are grateful to all concerned staff of Nippon Kaiji Kyokai who assisted us in the accomplishment of this study.

REFERENCES

1. Nippon Kaiji Kyokai (ClassNK), *Guidelines for Tanker Structures*, 2001.
2. Nippon Kaiji Kyokai (ClassNK), *Guidelines for Bulk Carrier Structures*, 2002.
3. Nippon Kaiji Kyokai (ClassNK), *Guidelines for Container Carrier Structures*, 2003.
4. N. Toki., A Study on the Determination of Design Wave Condition (2nd Report), *Transactions of the West-Japan Society of Naval Architects*, Vol. 93, pp. 121-133, 1997 (in Japanese).
5. H. Kawabe, S. Hibi, H. Tanaka, K. Shibazaki, and H. Sasajima, Contribution of Supposed Wave Condition on Long-term Distribution of Wave Induced Load (1st Report Relation between the Maximum Wave Induced Load and Suppose Wave Condition), *Journal of the Society of Naval Architects of Japan*, Vol. 186, pp. 319-339, 1999 (in Japanese).
6. Nippon Kaiji Kyokai (ClassNK), *Technical Guide Regarding the Strength Evaluation of Hull Structures*, 1999.
7. G. S. Baarholm and T. Moan, Estimation of Nonlinear Long-term Extremes of Hull Girder Loads in Ships, *Marine Structures*, Vol. 13, No. 6, pp. 495-515, 2000.
8. T. Shigemi and T. Zhu, Practical Estimation Methods of the Design Loads for Primary Structural Members of Tankers, *Marine Structures*, Vol. 16, No. 4, pp. 275-321, 2003.
9. T. Zhu and T. Shigemi, Practical Estimation Methods of the Design Loads for Primary Structural Members of Bulk Carriers, Marine Structures, Vol. 16, No. 7, pp. 489-515, 2003.
10. J. Fukuda, Theoretical Determination of Design Wave Bending Moments, *Japan Shipbuilding Marine Engineering*, Vol. 2, No. 3, pp. 13-22, 1967.
11. H. Mano and H. Ueno, A Simplified Estimation of Long-term Distributions of Various Random Variables Induced by Ocean

Waves, and a Study on the Influences of Operating Conditions on the Extremes, *Journal of the Society of Naval Architects of Japan*, Vol. 132, pp. 235-247, 1972 (in Japanese).

12. IACS Recommendation No. 34, Standard Wave Data, 2000.
13. T. Zhu, A. Kumano, T. Shigemi, and R. Matsunami, Consideration of Wave-induced Loads for Direct Strength Calculation under Extreme Waves, *Proceedings of the 21st International Conference on Offshore Mechanics and Arctic Engineering*. OMAE2002, Oslo, Norway, ASME, 2002.
14. R. Miyake, T. Zhu, and H. Kagemoto, On the Estimation of Wave-induced Loads Acting on Practical Merchant Ships by a Rankine Source Method, *Journal of the Society of Naval Architects of Japan*, Vol. 190, pp. 107-119, 2001 (in Japanese).
15. R. Miyake, T. Zhu, T. Shigemi, K. Iijima, and A. Kumano, Study on Wave-induced Torsional Loads for Practical Strength Assessment of Container Ships, *Proceedings of 9th Symposium on Practical Design of Ships and Other Floating Structures*, Luebeck-Travemuende, Germany, pp. 876-887, Seehafen Verlag, 2004.
16. M. Harada, Practical Evaluation of Buckling Strength of Ship Plating, *ClassNK Techical Bulletin*, Vol. 19, pp. 49-57, 2001.
17. N. Yamamoto and K. Matsuoka, Fatigue Assessment Method Considering an Effect of Mean Stress, *Journal of the Society of Naval Architects of Japan*, Vol. 190, pp. 499-505, 2001 (in Japanese).
18. N. Yamamoto and K. Ikegami, A Study on the Degradation of Coating and Corrosion of Ship's Hull Based on the Probabilistic Approach, *Journal of Offshore Mechanics and Arctic Engineering,* Vol. 120, pp. 121-128, 1998.