Design of Ship Hull Structures

A Practical Guide for Engineers

Bearbeitet von
Yasuhisa Okumoto, Yu Takeda, Masaki Mano, Tetsuo Okada

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Chapter 2
Structural Design Loads

2.1 Introduction

When a ship is sailing at sea, it is subjected to various load patterns with many magnitudes which cause deformation of its structure, as well as stresses. The structural designer needs to know the hull structure load features, as accurately as possible: direction of the working load, frequency of occurrence, distribution pattern on the hull structure and behavior in the time domain, etc. The first design step is to assume exact loads acting on the structure concerned, in order to estimate the structural strength in a reasonable way and consequently to develop the design.

In this chapter, the classification of loads being applied to a hull structure will be explained, then the features of typical load components will be described, and finally the method of estimating wave loads will be discussed.

When considering the load features where the load is transmitted gradually and continuously from a local structural member to an adjacent bigger supporting member, the best way to categorize loads on the hull structure is as follows:

- Longitudinal strength loads
- Transverse strength loads
- Local strength loads

(1) Longitudinal Strength Load: Longitudinal strength load means the load concerning the overall strength of the ship's hull, such as the bending moment, shear force and torsional moment acting on a hull girder. Since a ship has a slender shape, it will behave like a beam from the point view of global deformation. Now let's assume a ship is moving diagonally across a regular wave as shown in Fig. 2.1.1. The wave generates not only a bending moment deforming the vessel in a longitudinal vertical plane but also a bending moment working in the horizontal plane, because of the horizontal forces acting on side shell. In addition, the wave causes a torsional moment due to the variation of the wave surface at different sections along the ship's length. If the above longitudinal strength loads exceed the upper limit of longitudinal strength for the hull, the hull will be bent or twisted. Therefore the longitudinal strength load is one of the most important loads when calculating the overall strength of a hull structure.

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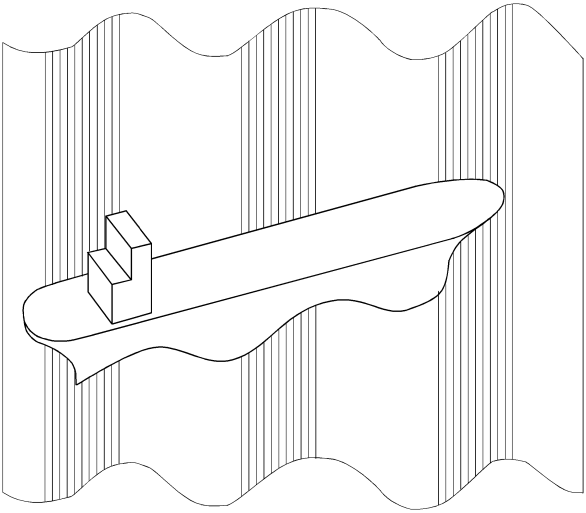

Fig. 2.1.1 Ship in oblique waves

(2) Transverse Strength Loads: The transverse strength loads represent the loads which act on transverse members and cause structural distortion of a cross section. Transverse strength loads include hydrostatic pressure on the outer shell, weight of cargo load working on the bottom structure, ballast water pressure inducing the deformation of the ballast tank, etc. For instance, let's imagine a transverse section of a ship floating in still water as illustrated in Fig. 2.1.2. This section is subjected to: (a) hydrostatic pressure due to surrounding water, (b) internal loading due to self weight and cargo weight. These loads are not always equal to each other at every point, consequently loads working on transverse members will produce transverse distortion as shown by the broken line in Fig. 2.1.2. When we consider transverse loads and longitudinal loads, the following characteristic is significant from the strength analysis point of view: The distortion due to longitudinal loads does not

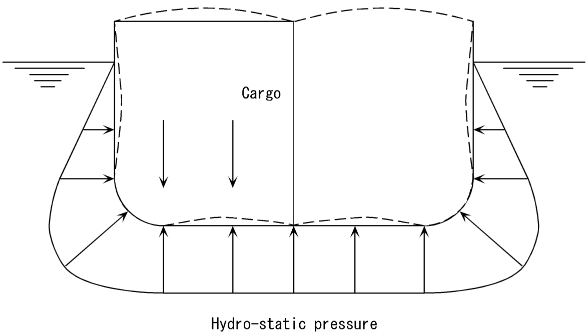

Fig. 2.1.2 Example of deformation due to transverse strength loads

affect the deformation of the transverse section. For example, the longitudinal bending moment or shear force can never have an influence on the distortion of the cross section. It is therefore necessary to recognize the transverse deformation of the ship structure due to the transverse load, independently from the deformation induced by a longitudinal load. Transverse strength loads are commonly used in cases where we investigate the strength of primary members, such as transverse rings, transverse web frames, etc.

(3) Local Strength Loads: The local strength loads include loads which affect the local strength members such as shell panels, stiffeners and connecting constructions between stiffeners.

The above load categories are so convenient that they are extensively used for practical design purposes. A load acting on the structure can be treated independently by considering the load transferring from a local structure to a bigger structure. For example, let's consider the case where the designer commences the design of a bottom structure as shown in Fig. 2.1.3. Firstly, the strength of bottom shell panels must be determined regarding lateral water pressure, secondly, the strength of longitudinal stiffeners, which support the subject panels, must be evaluated, thirdly, the strength of transverse webs holding stiffeners at their ends must be estimated and finally, the global strength of the bottom structure must be discussed. Investigations can be done separately for each member by only considering the magnitudes of the loads which are transmitted by each member.

This is a convenient concept, however, time-dependent relations between those simplified loads have been intentionally omitted. Therefore careful attention must be paid, particularly when analyzing the simultaneous response of the entire structure

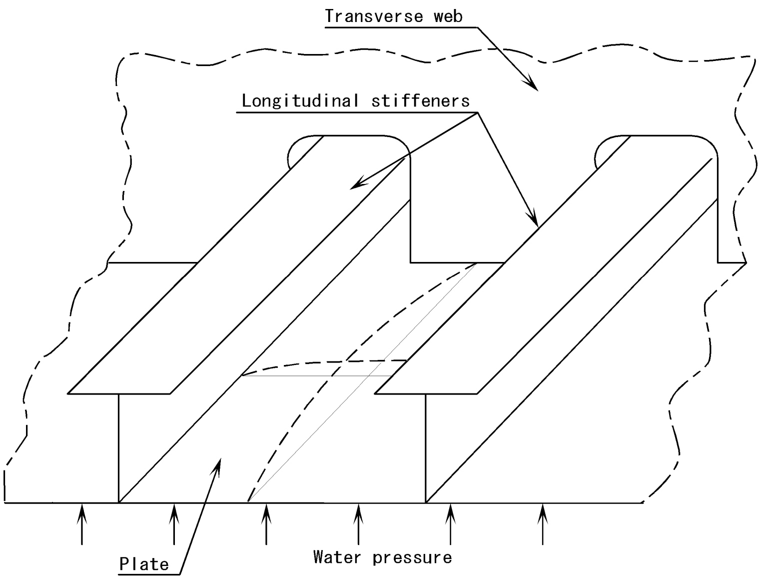

Fig. 2.1.3 Bottom structure under water pressure

to combined loads, because the phase of the loads plays an important roll when calculating the overall response.

2.2 Longitudinal Strength Load

Longitudinal strength loads are loads which affect the overall strength of a ship's hull girder, in which the ship is regarded as a beam or girder, because of it's slender profile. They are represented in terms of longitudinal bending moment, shear force and torsional moment. The longitudinal strength loads may be divided into two categories: static longitudinal loads and dynamic longitudinal loads.

Static longitudinal loads are induced by the local inequalities of weight and buoyancy in the still water condition. For instance, differences between weight and buoyancy in longitudinal direction cause a static bending moment and a static shear force, and asymmetrical cargo loading causes in a static torsional moment.

Dynamic longitudinal loads are induced by waves. When the ship is on top of a wave crest in head sea condition, it causes a "hogging" bending moment and a shear force. When in a wave trough a "sagging" bending moment and shear force are experienced, as indicated in Fig. 2.2.1. These loads act alternately on the hull girder as the wave progresses along the ship. In cases where the ship encounters oblique seas a dynamic torsional moment is produced.

The magnitude of the dynamic longitudinal load used in strength calculations of wave bending moment and wave shear force used to vary with each Classification Society. However, the rules were standardized by the IACS (International

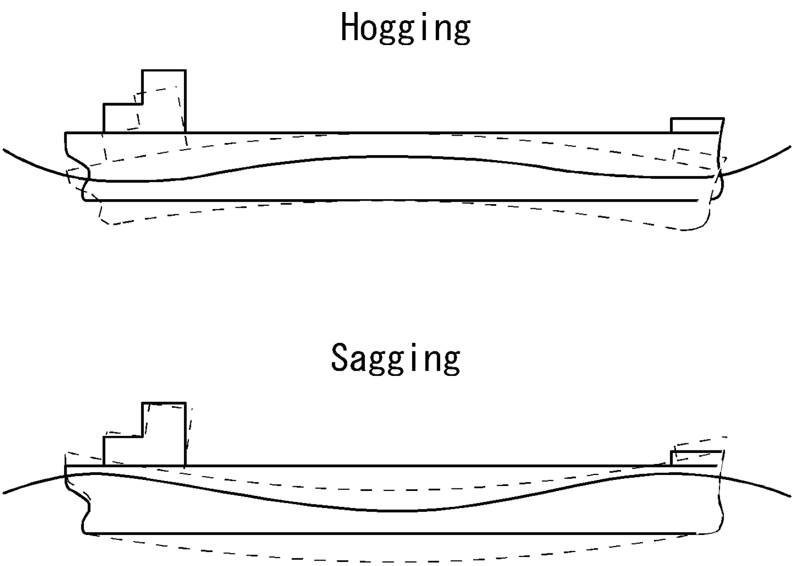

Fig. 2.2.1 Vertical bending due to waves

Association of Classification Societies) in the Unified Rule Requirement in 1989 and were accepted by all Classification Societies. For example, IACS specifies the wave bending moments with the following equations, which are common equations used by the major Classification Societies that belong to IACS:

$$Mw(+) = +0.19C_1C_2L_1^2BC_b' \qquad \text{(kN-m)} \tag{2.2.1}$$

$$Mw(-) = -0.11C_1C_2L_1^2B(C_b'+0.7) \qquad \text{(kN-m)} \tag{2.2.2}$$

where

$Mw(+)$: the wave bending moment of hogging
$Mw(-)$: the wave bending moment of sagging
C_1: the parameter determined by ship length

$$C_1 = \begin{cases} 10.75 - \left(\dfrac{300-L_1}{100}\right)^{1.5} & \mathrm{L_1} \leq 300\,\mathrm{m} \\ 10.75 & 300\,\mathrm{m} \leq \mathrm{L_1} \leq 350\,\mathrm{m} \\ 10.75 - \left(\dfrac{L_1-350}{100}\right)^{1.5} & 350\,\mathrm{m} \leq \mathrm{L_1} \end{cases} \tag{2.2.3}$$

C_2: distribution factor along ship length as specified in Fig. 2.2.2
L_1: ship length (m)
B: ship breadth (m)
C_b': block coefficient

The above dynamic longitudinal loads can be obtained by the long-term prediction method on the basis of ship motion calculations by strip theory. The details will be discussed in Sect. 2.4. The long-term prediction method means a method to predict a response statistically over a rather long period, e.g. the 20 years life cycle of a ship. So, instead of using the Classification Societies' Rules formulae to calculate the dynamic loads in the conventional way, the direct calculation method for practical design purpose has become more popular for its convenience and accuracy. The wave induced bending moment of IACS is determined in such a way that the magnitude of the bending moment is expected to be approximately equal to the maximum

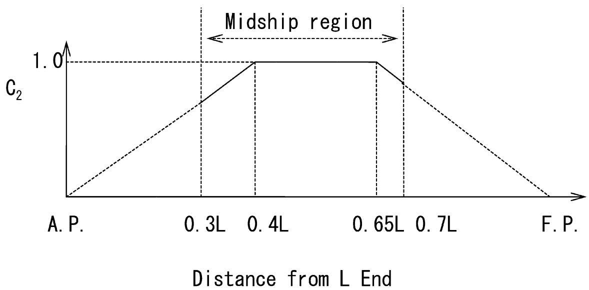

Fig. 2.2.2 Coefficient C2 : distribution factor

Fig. 2.2.3 Types of slamming impact of a ship

value once in 20 years, i.e. the expected probability of occurrence is: $Q = 1 \times 10^{-8}$. The IACS formulae were found to be reasonable with the aid of the above mentioned long-term prediction method carried out by several classification societies.

In the case of moderate seas the above prediction method, based on linear strip theory, is reliable enough to estimate the wave loads accurately. However, with

Fig. 2.2.4 Wave impact at sea

rough sea conditions this linear theory cannot be applied, since the calculated results of ship motion and dynamic loads are influenced by the wave impact force and/or by the non-linear effect of the vertical change of ship breadth at each cross section. These impact loads can contribute to the increase of longitudinal loads, for they may generate both an additional bending moment and shear force in the hull girder.

Wave impact loads can be divided into two loads: (a) impact force induced by slamming and (b) impact force of green seas on the deck.

Slamming occurs when the hull hits the water surface hard, when ship movement is severe, particularly in heave and pitching conditions. When the bottom emerges from the wave surface, "bottom slamming" is induced on the ship's bottom plating, as shown in Fig. 2.2.3. In the case of slamming on bow flare, it is called "bow flare slamming". Figure 2.2.4 shows also a container vessel subjected to wave impact in rough seas at the bow area.

If a ship's bow is pushed into the water in a severe downward pitch, the wave crest may come down on the forecastle deck, which may cause damage to the ship structure and deck machinery. This is called "deck wetness by green water."

2.3 Transverse Strength Load

Transverse strength loads denote the loads which cause distortion of transverse members due to unbalance of external and internal loads, including structural and cargo weights. These loads can be regarded as being independent of longitudinal strength loads, for the longitudinal loads only cause a ship to behave as a beam and they do not cause distortion of the transverse section. These loads are categorized as follows:

- Structural weight, ballast water weight and cargo weight
- Hydrostatic and hydrodynamic loads
- Inertia force of cargo or ballast due to ship motion
- Impact loads

(1) Structural weight, ballast water weight and cargo weight: These loads are dead loads, which mean constant loads that are time independent, induced by gravity at the centers of gravity of the members.

(2) Hydrostatic and hydrodynamic loads: The hydrostatic load is the static pressure from the water surrounding a transverse section, which acts on the hull structure as an external load. Another external load is the hydrodynamic load induced by the interaction between waves and the ship motion and subjects the outer shell of the ship to fluctuating water pressure. It is superimposed on the hydrostatic load and creates the total water pressure.

Each classification society gives the empirical formula for calculating the fluctuating external pressure by waves in a different way. For example, NK specifies the calculation form of the external water pressure by including the fluctuating pressure as shown in Fig. 2.3.1. In the figure, H_0, H_1, H_2 are the symbols representing the magnitude of fluctuating pressure distribution at the wave trough position below the static draft, at the wave crest position above the static draft and at the bottom base line respectively.

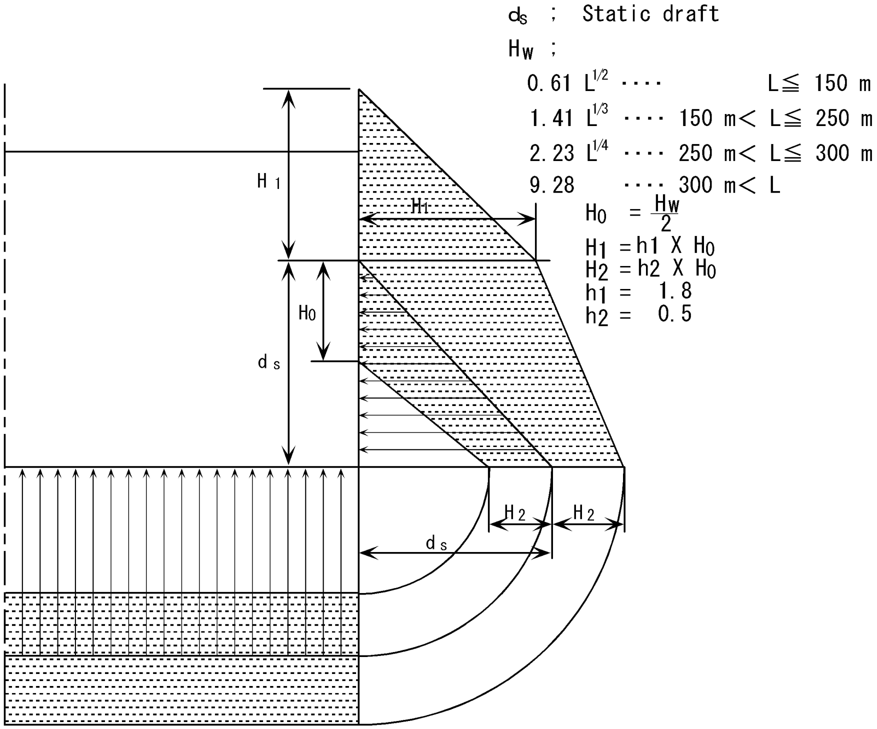

Fig. 2.3.1 Transverse strength calculation loads by NK

An alternative way to estimate the wave fluctuating pressure is to calculate it with the aid of the long-term prediction method which is also the case when calculating the longitudinal strength load which will be described hereafter. For practical purposes this method is accurate enough to be used in structural design.

(3) Inertia force of cargo or ballast due to ship motion: The inertia force is induced by the reaction force of self weight, cargo weight or ballast weight due to the acceleration of the ship motion. Assume that a tanker is rolling among waves in a fully loaded condition, then the cargo oil in the hold has a cyclic movement in the transverse direction. This must result in a fluctuating pressure of the hull structure of the tank due to the inertia force of the cargo oil movement. In addition, internal pressure is introduced not only by rolling but also by the ship's other motions, such as heaving, pitching, etc. A similar phenomenon can be observed when a cargo oil tank is partially filled.

The same long-term prediction method is applicable in the prediction of the internal pressure, since it gives an accurate prediction of the acceleration.

(4) Impact loads: There are two impact loads classified as transverse strength loads: slamming and sloshing.

Slamming may be categorized as a transverse strength load, as well as a longitudinal strength load. It means the impact force as the shell plating hits the water surface severely. Therefore, it generates not only a longitudinal load but also a load affecting the transverse strength simultaneously. Many ships are damaged by slamming, resulting in denting of shell plating, in particular the bottom forward shell plating. Wave impact pressure is an item for which the pure theoretical approach is very difficult, so experiments are necessary to estimate the impact pressure with reliable accuracy. Figure 2.3.2 denotes one of the test results from a dropping test of an inclined 2 dimensional bow structure model.

Sloshing is a phenomenon where the fluid movement in the tank gets into resonance with the ship motion and creates an impact force between the moving free surface of the fluid and the tank structure. Sloshing is caused by the movement of the fluid's free surface, therefore, if the tank is fully filled with fluid, sloshing will never happen since the free movement of the liquid's surface is restricted. When the level of the liquid reaches to a certain portion of the tank, the liquid resonates with the movement of the tank and then sloshing occurs.

The natural frequency of sloshing is determined by the tank dimensions and the level of the liquid. Figure 2.3.3 shows one of the experimental results of a sloshing

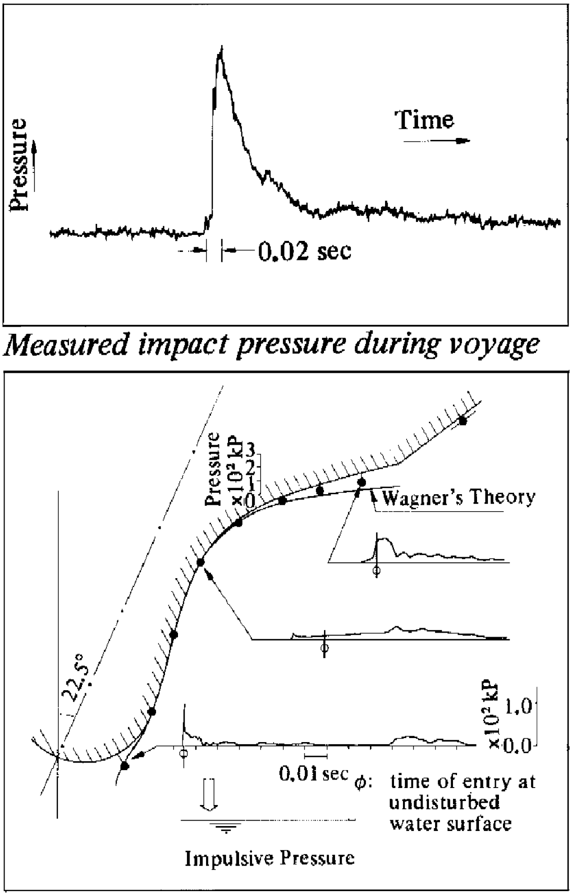

Fig. 2.3.2 Drop test results of inclined 2- dim. model

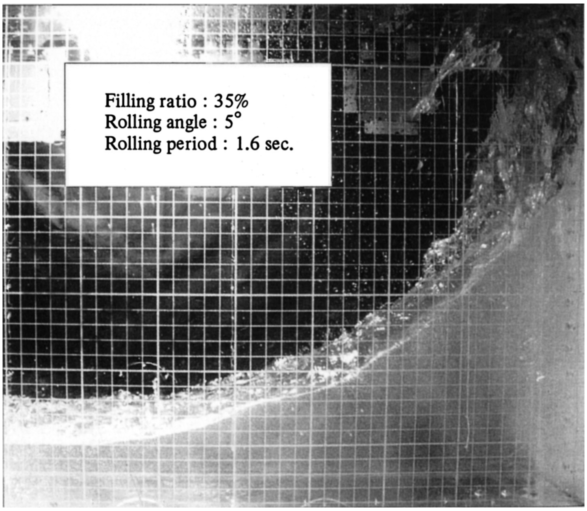

Fig. 2.3.3 Sloshing test of a rectangular tank

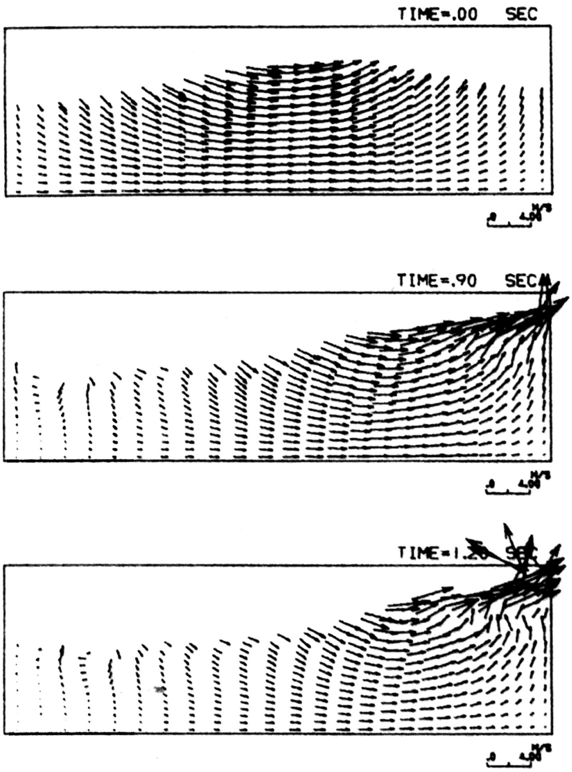

Fig. 2.3.4 Computer simulation of liquid sloshing in a tank

test of a rectangular tank model and Fig. 2.3.4 indicates the result of a computer simulation program utilizing the finite difference technique.

2.4 Ship Response Calculation in Waves

2.4.1 Introduction

In order to obtain an accurate estimation of wave induced loads, the designer has to know an exact wave load calculation method. In this article the evaluation procedure of wave loads is briefly introduced; for a more detailed discussion the reader is referred to [8–10]. A prediction method of wave loads and ship responses has been developed on the basis of the strip method, and it was found that the calculated result can be used for the practical design of conventional vessels. The ordinary evaluation procedure follows the calculation steps as below:

– Calculation of ship responses among regular waves by the strip method
– Short-term prediction method for ship responses among irregular waves
– Long-term prediction method for ship responses among irregular waves

2.4.2 Strip Method

A ship has a long and slender hull shape in comparison with its breadth and depth. Taking advantage of the above assumption, fluid motion around hull surface due to ship motion can be regarded as if it moves in cross sectional plane. In other words, the fluid force can be obtained by integrating the force acting on transverse strips delivered as shown in Fig. 2.4.1; consequently the interaction force between

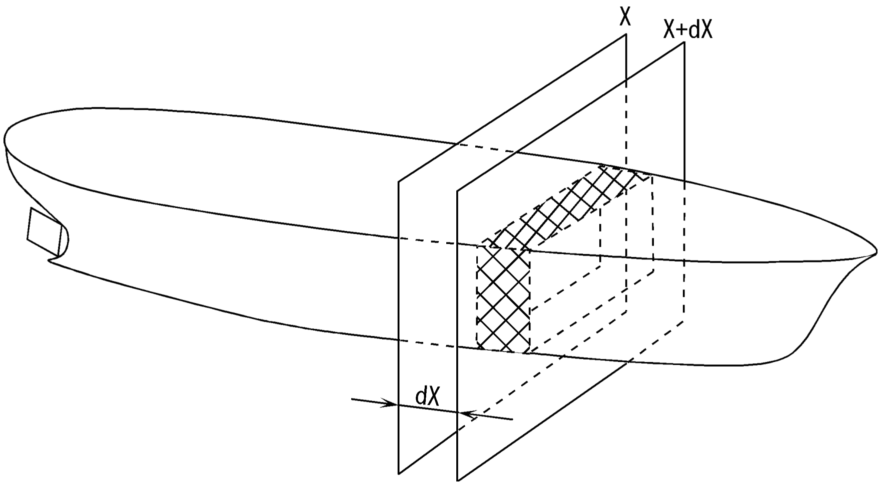

Fig. 2.4.1 Definition of ship's strip

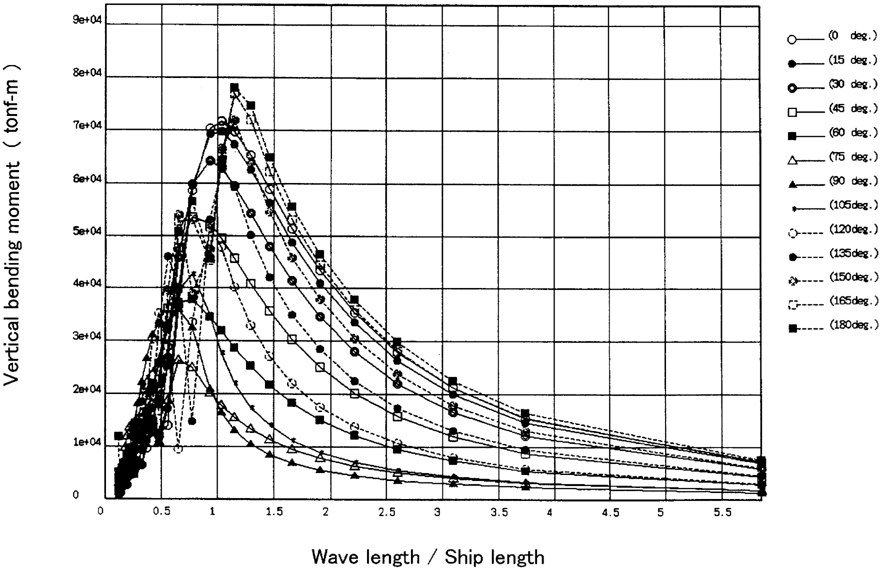

Fig. 2.4.2 Response function of vertical wave bending moment (150,000 DWT tanker)

each strip is neglected. The strip method is utilized to calculate ship motion, wave induced longitudinal strength loads and wave pressure distribution around the hull in regular waves. An example of the calculation results is presented in Fig. 2.4.2 and it shows the response functions due to a vertical bending moment at midship of double hull tanker of 150,000 DWT in regular waves [11]. According to the figure, it can be seen that the maximum bending moment occurs in the head sea condition, where the wave length is almost same as ship length, i.e. wave length/ship length = 1.0.

2.4.3 Short-Term Prediction

A short-term prediction method is useful to evaluate the ship's response in irregular waves by the statistical prediction theory. Short-term means a short period, say 30 min or so, where the significant wave height and the average wave period are considered to be constant. This prediction method is used for calculating the ship's response over a relatively short period of time in terms of ship accelerations, relative wave height, deck wetness, slamming, etc.

Although the waves at sea are not regular waves, these waves can be dealt with by a combination of regular waves having various frequencies and various heights. If the relationship between wave height and frequency of irregular waves is given in spectrum form and the response function of the ship in regular waves is known, then the spectrum of the ship response against irregular waves can be predicted with the following equation:

$$S'(\omega,\gamma) = S'_w(\omega,\gamma)\cdot|A(\omega,\mu)|^2 \tag{2.4.1}$$

where

$S'(\omega,\gamma)$: power spectra of ship response,
$S'_w(\omega,\gamma)$: power spectra of component wave in the γ-direction,
$A(\omega,\mu)$: ship's response function in regular wave to component wave in the μ-direction,
δ: angle between ship's course direction and average wave direction of irregular waves as defined in Fig. 2.4.3
γ: angle between average wave direction and component wave direction of irregular waves
$\mu = \delta + \gamma$: angle between ship's course direction and component wave direction of irregular waves
ω: circular frequency

The standard deviation R of the ship's response in the δ-direction among irregular waves can be obtained by integrating Eq. (2.4.1) for all frequencies ω and for all heading angles γ as in the form:

$$R(\delta)^2 = \int_{-\pi}^{\pi}\int_0^{\infty} S^{\eta}_w(\omega,\gamma)\cdot|A(\omega,\delta+\gamma)|^2 d\omega\cdot d\gamma \tag{2.4.2}$$

Although several types of spectrum functions $S'_w(\omega)$ of irregular waves are proposed, the Modified Pierson-Moskowitz wave spectrum, which was proposed in the second ISSC (International Ship Structure Committee) held in 1964, is usually applied for practical design purposes to express the long crested wave. These are determined by only two parameters, the average wave period and the significant wave height. The ISSC's wave spectrum is in the following form:

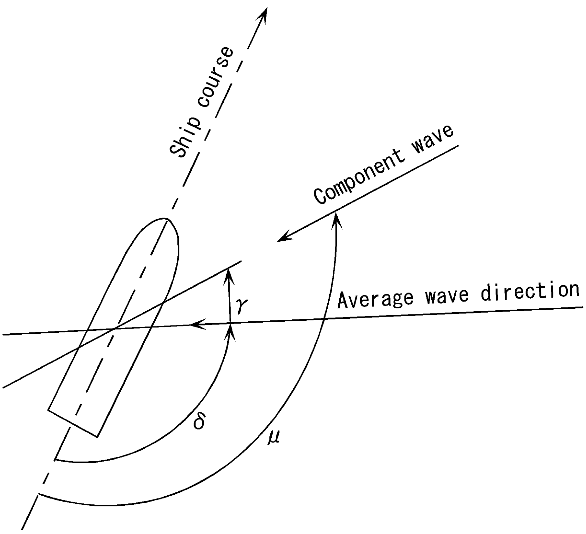

Fig. 2.4.3 Definition of ship's course snd wave incident direction

$$S'_w(\omega)/H^2 = 0.11\omega_1^{-1}(\omega/\omega_1)^{-5} \cdot \exp[-0.44(\omega/\omega_1)^{-4}] \quad (2.4.3)$$

where

H: significant wave height
$\omega_1 = 2\pi/T$
T: average wave period

This spectrum looks as illustrated in Fig. 2.4.4. When the effect of short crested waves must be taken into account, it is often assumed that the density of wave power is given by a $\cos^2\gamma$ distribution, where the heading direction of the average wave varies from $-\pi/2$ to $+\pi/2$.

Once the Standard Deviation R of the ship's response is obtained, a short-term prediction can be made by assuming that the probability distribution of the extreme response will follow Rayleigh's Distribution, that is:

$$\begin{aligned} \text{Average} &= 1.25\text{R} \\ \text{Average of 1/3 max.} &= 2.00\text{R} \\ \text{Average of 1/10 max.} &= 2.55\text{R} \\ \text{Expect of 1/100 max.} &= 3.22\text{R} \\ \text{Expect of 1/1000 max.} &= 3.87\text{R} \end{aligned} \quad (2.4.4)$$

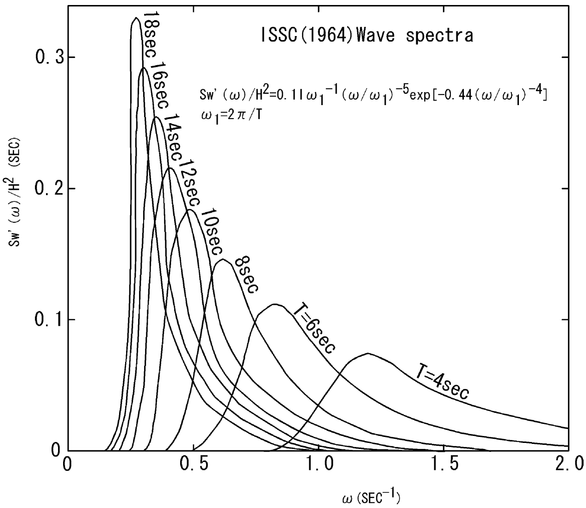

Fig. 2.4.4 Modified Pierson-Moskowitz wave spectra (ISSC spectra)

2.4.4 Long-Term Prediction

The long-term prediction is a method to predict statistically the ship's response in irregular waves over a rather long period of time, such as 20 years of the life cycle of a ship. This method can be applied to cases such as the prediction of the maximum bending moment in 20 years, or of the fatigue damage life, etc. The prediction procedure is explained in Fig. 2.4.5. Once the Standard Deviation $R(\delta)$ of the ship response is obtained by the short-term prediction, it is possible to calculate the excess probability $Q(r_1, \delta)$ by providing the ship's wave data over the specified life time in the following equation:

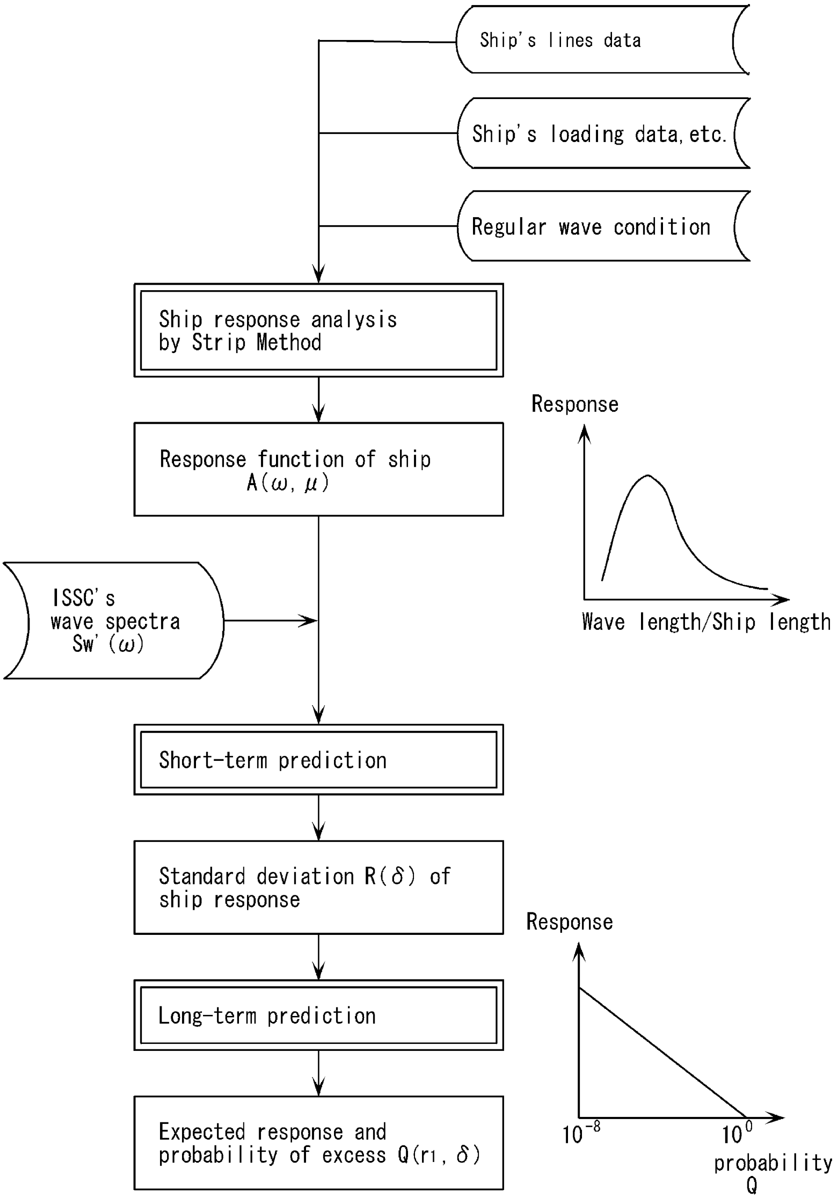

Fig. 2.4.5 Procedure of long-term prediction

$$Q(r_1, \delta) = \int_0^\infty \int_0^\infty \exp\left\{-\frac{r_1^2}{2R^2(H_w, T_W, \delta)}\right\} \cdot p(H_w, T_W) dH_w \cdot dT_{ww} \quad (2.4.5)$$

where

H_w: significant wave height
T_w: average wave period
$p(H_w, T_W)$: probability of wave occurrence in the specified sea area

It is therefore possible to obtain the probability of the occurrence that an extreme response may exceed the specified value r_1:

$$Q(r_1) = \int_0^{2\pi} Q(r_1, \delta) \cdot p^* d\delta \quad (2.4.6)$$

where

$Q(r_1)$: probability of occurrence
$p^*(\delta)$: probability density function of the ship's course direction

Figure 2.4.6 shows an example of a long-term prediction with regard to a vertical bending moment at midship of 150,000 DWT, for a double hull tanker sailing all over the world.

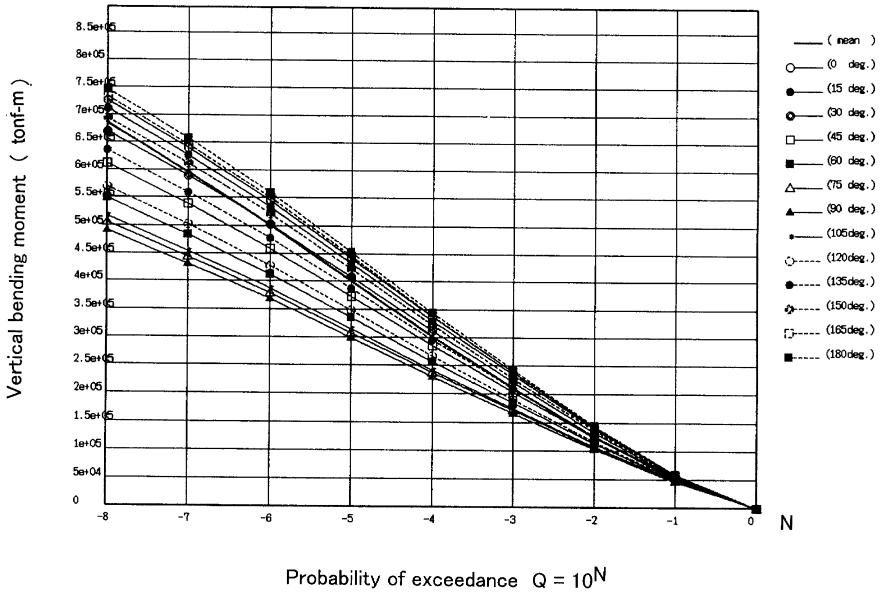

Fig. 2.4.6 Long-term prediction of vertical wave bending moment (150,000 DWT tanker)