Proceedings of OMAE2006
25th International Conference on Offshore Mechanics and Arctic Engineering
June 4-9, 2006, Hamburg, Germany

OMAE2006-92233

# FULL-SCALE MEASUREMENTS ON HULL RESPONSE OF A LARGE-CONTAINER SHIP IN SERVICE

**Kenichiro Miyahara**
**Nippon Kaiji Kyokai (ClassNK), Japan**

**Ryuju Miyake**
**Nippon Kaiji Kyokai (ClassNK), Japan**

**Norikazu Abe**
**Nippon Kaiji Kyokai (ClassNK), Japan**

**Atsushi Kumano**
**Nippon Kaiji Kyokai (ClassNK), Japan**

**Masanobu Toyoda**
**IHI Marine United Inc., Japan**

**Yoshiyuki Nakajima**
**IHI Marine United Inc., Japan**

## ABSTRACT

In order to investigate hull responses of post-Panamax container ships in the actual sea, full-scale measurements on hull responses of a post-Panamax container ship in service were conducted. In linear wave domain, the probability density distributions of hull responses obtained by full-scale measurements were compared with the Rayleigh distributions to check on the range of the applicability, and comparisons with the long-term distributions of the longitudinal stress obtained by full-scale measurements and the direct structural analyses based on the wave loads analyzed by using the linear 3D Rankine source method were made to verify the accuracy. In non-linear wave domain, the measured longitudinal stresses showed the asymmetry of vertical bending moment. The long-term distributions of hull responses, which have the high harmonic components, obtained by full-scale measurements were compared with the numerical results analyzed by using non-linear methods to investigate the non-linearity on hull responses of container ship.

Keywords: container ship, full-scale measurement, hull response, Rankine source method, non-linearity

## INTRODUCTION

The development of container ships seems to have been accelerated in recent years after the first post-Panamax container ship appeared in 1988, and a lot of post-Panamax container ships go into service. The increased size causes greater challenges in technology aspects. Warping stress and deformation of deck structure due to wave-induced torsional loads, bow flare impact, whipping and so on are important issues that need to be addressed to have a safe and well functioned ship. Although the strength assessment is possible by employing wave load analysis and FEM in combination with statistical methods like short-term and long-term prediction methods to predict the largest response, the accuracy of wave-induced moment evaluation is requirement and the number of steps taken for the calculations is large and the numerical procedures are complex. Therefore, some authors conducted comprehensive tank tests to develop rational and practical estimation method of the wave loads acting on container ships (Miyake et al, 2004), and proposed a practical method for torsional strength assessment which used the entire-ship FE models (Iijima et al, 2004). Using this method will lead to more appropriate assessment of torsional strength of container ships without conducting complex wave load analyses.

However, full-scale measurements on hull responses of post-Panamax container ships in service have hardly been reported, and there still remain some problems such as warping stress, asymmetry of vertical bending moment, bow flare impact, whipping and so on in the actual sea. Then, we have measured hull responses of a post-Panamax container ship in Japan-Europe route for two and a half years. We report the results of the full-scale measurements.

## FULL-SCALE MEASUREMENTS

Full-scale measurements were conducted for the post-Panamax container ship, as pictured in Fig. 1. The principal particulars of the vessel are shown in Table 1. The vessel shuttles Japan-Europe route linking Japan, Hong Kong, Singapore, Suez Canal and Europe in about two months.

**Fig. 1 6,400 TEU Post-Panamax Container Ship**

**Table 1 Principal Particulars**

| | |
|---|---|
| Length, between perpendiculars (Lpp) | 281.4m |
| Breadth (B) | 40.0m |
| Depth (D) | 24.2m |
| Draft (d) | 12.5m |
| Speed (Vs) | 25.6knots |

The measurements on thirty two measuring items such as seven longitudinal stresses on upper deck and the lowest part of L.BHD, bow flare impact pressures, three accelerations at bow, six degrees of motion at engine room (E/R), wave height, vessel speed, wind speed and ship position were conducted. For operation, weather and sea conditions, the shipmaster submitted the log book and stability report to the authors. Fig. 2 shows the arrangement of longitudinal stress sensors and wave height meter. The wave height meter system consists of a relative wave height sensor unit, an accelerometer, a connections box, and a signal processor. The accelerometer is used to remove ship motion from the relative wave height measurement. This sensor is known to indicate smaller value due to local wave disturbance. The wave height and encountering wave period were obtained by the measured raw data of wave amplitude.

We measured hull responses of the post-Panamax container ship for two and a half years, the measurements were conducted automatically for twenty minutes in every two hours. The measurements except the one on the bow flare impact pressures were sampled at 10Hz. The temperature effect is disregarded by setting the mean value of the measurement data as baseline value. In this report, we mainly report the results of the longitudinal stress.

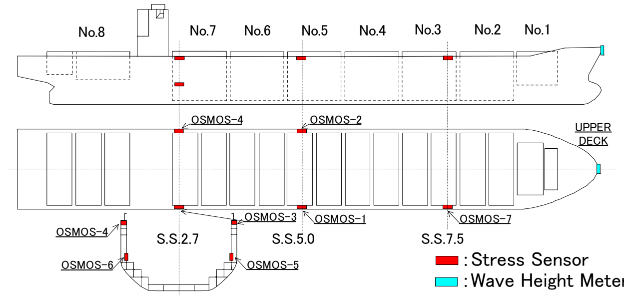


**Fig. 2 Arrangement of Sensors and Meter**

## Sea and Operation Conditions

The maximum Beaufort wind scale (B.S.) was 10 and the maximum swell height was 6.0m for the measurement period, and 80% of the measured data were 5 or less in B.S. and 2.0m or less in swell height. The comparison with the frequency distribution of the measured wave height and the wave data of global wave statistics (British Maritime Technology, Japan-Europe route, whole year) is shown in Fig. 3. The frequency of the measured wave height was clearly higher than the one of the global wave statistics in the lower wave height range.

The relation between wave height and ship speed and the histogram of encountered wave in each wave height obtained by the logbook are shown in Fig. 4 and Table 2, respectively. It noticed from this figure and table that the frequency of head sea increased and ship speed was reduced as wave height increased. Because the shipmaster changed ship speed and course to ease ship motions.

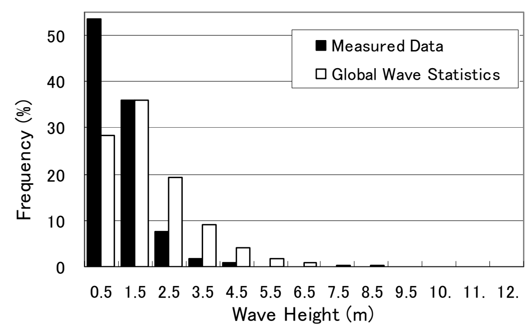


**Fig. 3 Frequency of Wave Height**

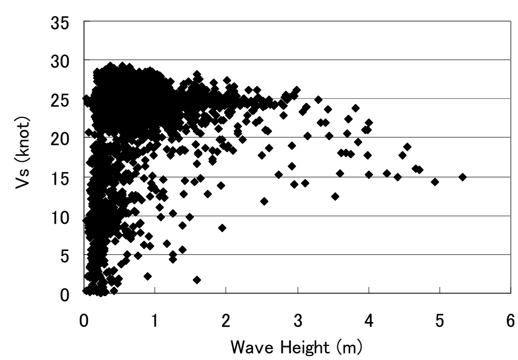


**Fig. 4 Wave Height vs. Ship Speed**

**Table 2 Histogram of Encountered Wave**

| Hw (m) | HEAD | BOW | BEAM | QUARTER | FOLLOW |
|---|---|---|---|---|---|
| 1 | 0.325 | 0.130 | 0.221 | 0.132 | 0.193 |
| 2 | 0.336 | 0.157 | 0.218 | 0.100 | 0.190 |
| 3 | 0.357 | 0.151 | 0.283 | 0.068 | 0.142 |
| 4 | 0.342 | 0.063 | 0.369 | 0.099 | 0.126 |
| 5 | 0.351 | 0.263 | 0.211 | 0.053 | 0.123 |
| 6 | 0.583 | 0.167 | 0.167 | 0.083 | 0.000 |

The frequencies of ship speed, mean draft and metacentric height (GM) are shown in Fig. 5. The vessel was stably navigated at the speed of 24-26 knot and decelerated to the speed of 15-22 knot in rough sea. The mean draft was 10m or less and the metacentric height was 3m or more in light load condition, the vessel was navigated at about design draft.

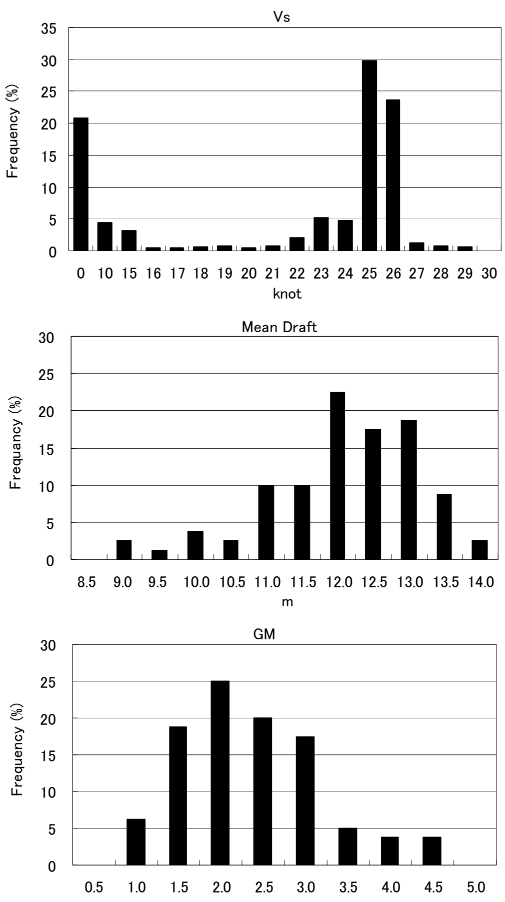


**Fig. 5 Frequency of Ship Speed, Mean Draft and GM**

## MEASUREMENT RESULTS AND ANALYSIS

The measured data were analyzed with low-pass filter to remove high frequency components such as stress due to whipping of the structure. The measured data in harbors, the Suez Canal and so on were removed by setting the threshold values of wave height and vessel speed.

### Decomposition of Longitudinal Stresses

The four longitudinal stresses on upper deck and the lowest part of L.BHD at the square station (S.S.) 2.7 in Fig. 2 were measured. These measured longitudinal stresses $\sigma_{CS}$ are decomposed to vertical bending stresses $\sigma_{VB}$, horizontal bending stresses $\sigma_{HB}$, warping stresses $\sigma_{WS}$ and axial stresses $\sigma_A$. Then, these measured stresses are assumed that the above-mentioned four stress components were combined, the longitudinal stresses are represented by the four stress components as the following equation.

$$\begin{Bmatrix} \sigma_{CS1} \\ \sigma_{CS2} \\ \sigma_{CS3} \\ \sigma_{CS4} \end{Bmatrix} = \begin{bmatrix} \alpha_1 & \beta_1 & \gamma_1 & \eta_1 \\ \alpha_2 & \beta_2 & \gamma_2 & \eta_2 \\ \alpha_3 & \beta_3 & \gamma_3 & \eta_3 \\ \alpha_4 & \beta_4 & \gamma_4 & \eta_4 \end{bmatrix} \begin{Bmatrix} M_V \\ M_H \\ M_T \\ F_A \end{Bmatrix} \quad (1)$$

where $\sigma_{CS}$ are the measured longitudinal stresses, coefficient ($\alpha$, $\beta$, $\gamma$, $\eta$) are responses per each unit load which are determined by FE analysis, and $M_V$, $M_H$, $M_T$, $F_A$ are vertical bending moment, horizontal bending moment, torsional moment and axial force, respectively.

### Short-term Distribution

It is known well that the probability density distribution of hull response is identical with the Rayleigh distribution. The probability density distributions of the hull responses have the first wave component having the same period as encountering wave period were compared with the Rayleigh distributions. The comparison with the vertical bending stress and the Rayleigh distribution at the S.S.2.7 is shown in Fig. 6 as an example. The measured data show good agreement with the Rayleigh distribution. Therefore the maximum value, the significance value and the mean value of short-term distributions obtained by full-scale measurements show good agreement with the theoretical results obtained by function of the standard deviation, as shown in Fig. 7.

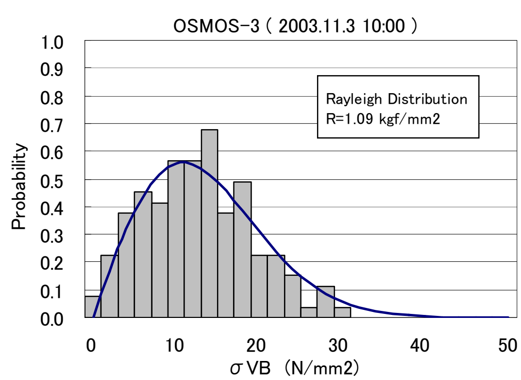


**Fig. 6 Probability Distribution of Longitudinal Stress**

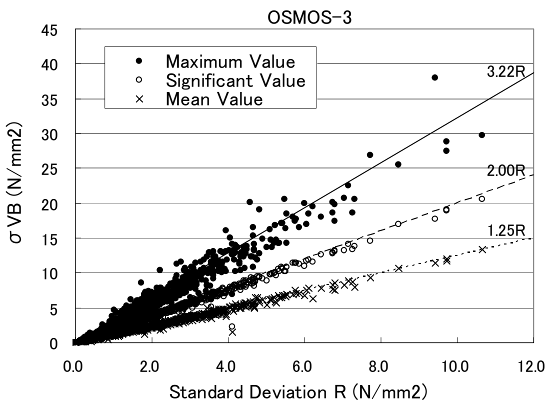


**Fig. 7 Maximum, Significant and Mean Stress**

## Short-term and Long-term Prediction

Short-term and long-term predictions were made on the response functions of vertical bending stress, horizontal bending stress and warping stress except the axial stress. The wave loads were analyzed by using the linear 3D Rankine source method which can consider the three-dimensional effect because the horizontal bending moment and the torsional moment analyzed by using the strip method for large container ships tends to overestimate (Miyake et al, 2004). The conditions used for analyzing wave loads are full load conditions (GM=1.15m and GM=2.0m). Structural responses of the container ship under the wave loads are analyzed by using global finite element structural model. When making the short-term and long-term predictions, the ISSC-1964 wave spectra (directional distribution: $\cos^2\theta$) and the wave data of global wave statistics were used, respectively. Long-term predictions were made by using the method proposed by Fukuda (1967). The measured stresses have the first wave component having the same period as encountering wave period to compare with the short-term and long-term predicted values based on the linear Rankine source method.

The standard deviations of the decomposed stress components obtained by the full-scale measurement were compared with the short-term predicted values analyzed by using the Rakine source method and FEM at the S.S.2.7 in head sea of short-crested irregular waves. The numerical results in GM=1.15m are shown in Fig. 8 as an example, because the numerical results in GM=1.15m were almost the same as the ones in GM=2.0m, there is little difference due to GM. The abscissas show the wave period and the ordinates show the standard deviation of the stress per unit significant wave height. The short-term predicted values of horizontal bending stress and warping stress are good agreement with the measured stresses, while the short-term predicted values of vertical bending stress are a little lower than the measured stresses. Therefore the short-term predicted values of longitudinal stress are a little lower than the measured stresses.

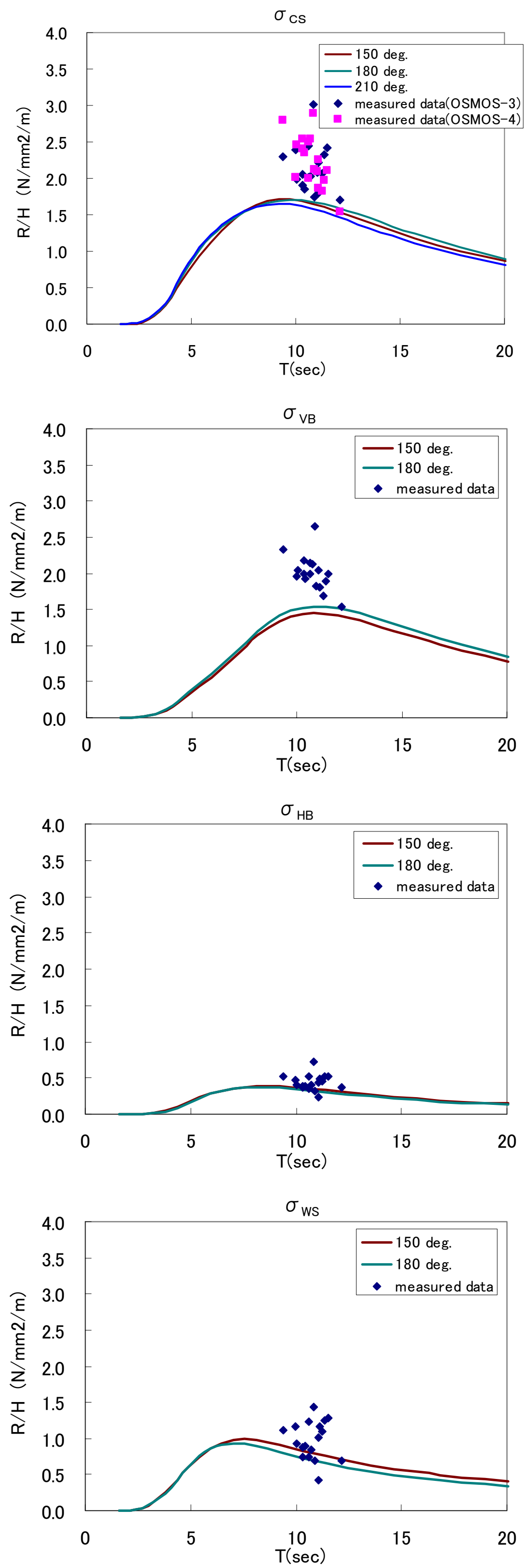


**Fig. 8 Standard Deviation of Stresses (GM=1.15m)**

The comparison with the stress components at the S.S.2.7, 5.0 and 7.5 and the long-term predicted values (All Heading) considering the influence of the encounter wave height is shown in Fig. 9. The measured warping stress was about 70 percent of the measured vertical bending stress at the S.S.2.7. The long-term predicted values show good agreement with the measured stresses although the long-term predicted values of vertical bending stress is a little lower than the measured stresses at the S.S.2.7. The measured longitudinal stress becomes larger than the long-term predicted value of longitudinal stress as close to the bow. The discrepancy is attributed to the nonlinear characteristics of vertical bending moment due to wave height.

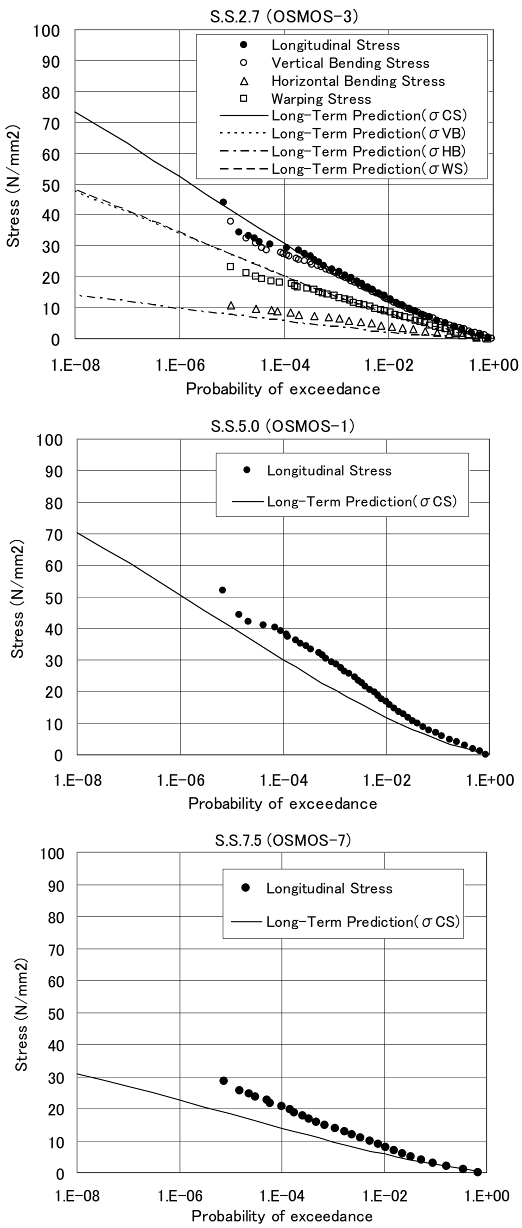


**Fig. 9 Long-term Predicted Values of Stress**

## Correlation Coefficient

When assessing the torsional strength of hull girder of container ships, vertical bending stress, horizontal bending stress and stresses in still-water are combined with warping stress to estimate the total hull girder stress. This method is to combine the stress components in terms of a quadratic expression with correlation coefficients as follow (e.g. ClassNK, 2003).

$$\sigma_{CS} = \sqrt{(\sigma_{VB})^2 + \left(\sigma_{HB}{}^2 + 2\rho\sigma_{HB}\sigma_{WS} + \sigma_{WS}{}^2\right)} \quad (2)$$

where $\rho$ is the correlation coefficient between horizontal bending stress and warping stress. For example, the coefficients are –1.0 at positions from 0.15$L$ to 0.75$L$ and come closer to 1.0 at bow part and stern part, while the coefficients are 0.0 at position around 0.2$L$-0.3$L$ in the ClassNK guideline. This irregularity is due to the constraints of the rigid E/R structure.

Then, we investigated the correlation coefficients between vertical bending stress, horizontal bending stress and warping stress. The correlation coefficients between two stress components such as warping stress and horizontal bending stress are assumed to be determined by the standard deviations $R$ of these stress components. The correlation coefficient $\rho$ is represented as the following equation.

$$\rho_{12} = \frac{R_3^2 - (R_1^2 + R_2^2)}{2R_1R_2} \quad (3)$$

where $R_1$, $R_2$, are the standard deviations of two stress components, $R_3$ is standard deviations of the stress combined two stress components and $\rho_{12}$ are the correlation coefficient between two stress components.

The correlation coefficient between warping stress and horizontal bending stress in front of E/R is shown in Fig. 10 (a). The abscissas show the standard deviation of stress per unit significant wave height and the ordinates show the correlation coefficient. The correlation coefficient between warping stress and horizontal bending stress tends to have two values about 0.0 and about -0.8 as the standard deviation of warping stress per unit significant wave height increases. The correlation coefficient 0.0 is important and -0.8 isn't important on strength assessment of container ship.

The correlation coefficient between vertical bending stress and the stress combined warping stress and horizontal bending stress in front of E/R is shown in Fig. 10 (b). The correlation coefficient between vertical bending stress and combined stress is settled to 0.0 as the standard deviation of combined stress per unit significant wave height increases. The correlation coefficients obtained by full-scale measurement are good agreement with the ClassNK guideline.

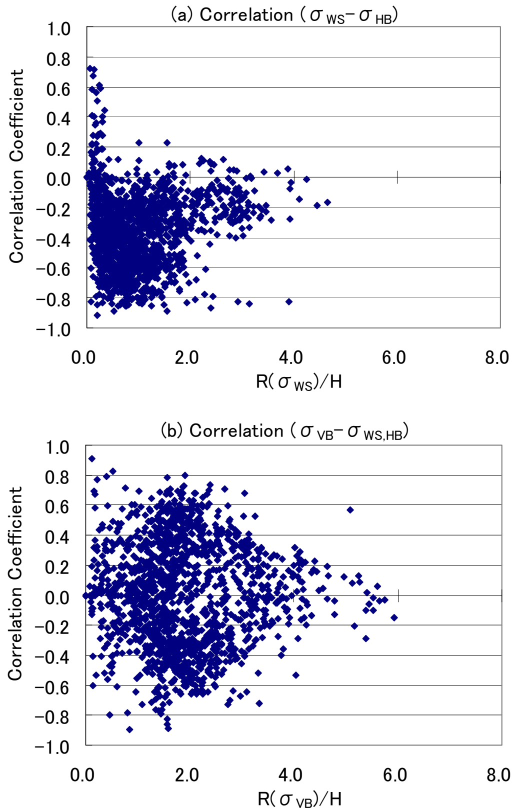


**Fig. 10 Standard Deviation of Stresses**

## Asymmetry of Vertical Bending Stress

It has been known that sagging moment is bigger than hogging moment on high speed and fine ship, e.g. container ship. The measured stress which has the third wave components having a third period as encountering wave period showed the asymmetry of vertical bending moment. Such non-linear characteristic were also confirmed in the experiment of container ship (e.g. Watanabe, 1989). The long-term distributions of the measured vertical stress were at the S.S.2.7 and the measured longitudinal stresses at the S.S. 5.0 and 7.5 compared with the numerical results of vertical bending stress, which have the third wave components having the same period as encountering wave period were analyzed by using the non-linear methods to investigate the non-linearity on hull responses of container ships, as shown in Fig. 11. When making the short-term and long-term predictions, the ISSC-1964 wave spectra (directional distribution: $\cos^2\theta$) and the wave data of global wave statistics were used, respectively. Long-term predictions of the numerical analysis were made by using the RAOs (response amplitude operator) in wave angle $\chi$= 180deg. and Hw=10.0m which is the maximum wave height for the measurement period, because the frequency of head sea condition increases as wave height increase, as shown in Table 2. Sagging and hogging sides are taken from the mean value of wave-induced components.

In the figure, "Long-term Prediction (Rankine)" and "Long-term Prediction (SR-SLAM)" denote the numerical results analyzed by the non-linear Rankine source method and the non-linear strip method (Yamamoto, 1978) in head sea, respectively. The asymmetry gradually increases below the exceedance probability Q=$10^{-3}$ of vertical bending stress. The numerical results are good agreement with the measured data. It was confirmed that the numerical methods such as the non-linear Rankine source method and strip method considering the nonlinear characteristics of vertical bending moment due to wave height are effective methods for estimating the vertical bending stress. However, it is required to improve the accuracy of evaluation of whipping and effect of bow flare.

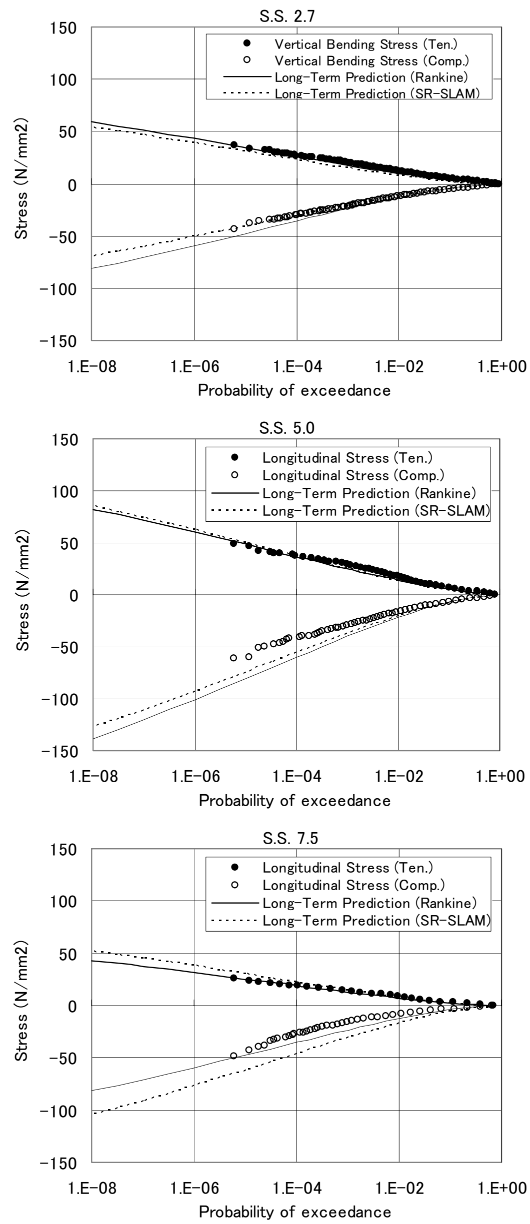


**Fig. 11 Long-term Predicted Value of Stress**

## CONCLUSIONS

Full-scale measurements were conducted for the post-Panamax container ship in Japan-Europe route. Some of the results were compared with those analyzed by Rankine source methods and non-linear strip method. The findings of the study can be summarized as follows.

(1) The linear Rankine source method which can properly consider the three dimensional effect is an effective method for estimating wave loads.

(2) Warping stress is 70% of vertical bending stress. Horizontal bending stress is smaller than vertical bending stress and warping stress.

(3) The correlation coefficient between warping stress and horizontal bending stress is settled to 0.0 as the standard deviation of warping stress per unit significant wave height increases. Similarly, the correlation coefficient between vertical bending stress and the stress combined the above-mentioned two stress components is 0.0.

(4) The asymmetry of the vertical bending stress can be estimated well by the non-linear methods which consider the nonlinear characteristics of vertical bending moment due to wave height.

## ACKNOWLEDGMENTS

The authors would like to acknowledge the cooperation of Mitsui O.S.K. Lines. Full-scale measurements have been carried out as a part of the joint research project among IHI Marine United and Nippon Kaiji Kyokai. The authors wish to gratefully acknowledge the effort of all people associated with this work.

## REFERENCES

Miyake, R., 2004, ”On the Estimation of Torsional Loads Acting on a Large-Container Ship”, Proceedings of 25th Symposium on Naval Hydrodynamics, CD-ROM, MiyakeR.pdf.

Iijima, K., 2004, ”A Practical Estimation Method of Container Ships”, PRADS, Vol. 1, pp. 79-86.

British Maritime Technology, ”Global Wave Statistics”

Fukuda, J., 1967, ”Theoretical Determination of Design Wave Bending Moments”, Japan Shipbuilding and Marine Engineering, Vol. 2, pp. 13-22.

ClassNK, 2003, ”Guidelines for Container Carrier Structures”, Nippon Kaiji Kyokai (ClassNK)

Watanabe, I., 1989, ”Effects of Bow Flare Shape to the Wave Loads of a container ship, Journal of the society of Naval Architects of Japan, Vol. 166, pp. 259-266.

Yamamoto, Y., 1978, ”Motion and Longitudinal Strength of a Ship in Head Sea and the effects of Non-Linearities, Journal of the Society of Naval Architects of Japan, Vol. 143, pp. 179-187.