論　文

大韓造船學會誌
第26卷 第1號 1989年 3月
Journal of the Society of
Naval Architects of Korea
Vol. 26, No. 1, March 1989

Full-Scale Measurement of Pure Car Carrier

by
Jin S. Park*, Oi H. Kim* and Zae K. Chung*

자동차 운반선에 대한 실선 계측

박진수*, 김외현*, 정재구*

Abstract

This paper presents the results of full-scale structural measurements of 4,800 unit pure car carriers "HYUNDAI NO.103" and "HYUNDAI NO.105" on one voyage respectively for each ship, especially in order to investigate the local strength of partial bulkhead above free-board deck.

With the measured data, the short-term frequency analyses have been performed. The results show that the wave-induced stresses follow, on the whole, well the Rayleigh distribution. In addition, it has been found from the measured data that transverse local stresses at bulkhead section have a very close relation with the acceleration in athwartship direction.

Finally, the long-term analysis has been attempted by using the following two statistical distributions mainly in order to estimate the maximum stress amplitude at the corners of partial bulkhead.

1) Exponential distribution of cycles of stress amplitude
2) Double exponential distribution of extreme values of stress amplitude for each short-term analysis

The results of these two cases show a good agreement with each other. For example, the estimated maximum stress amplitude for 10 years at port-side corner of Fr. 132 partial bulkhead is 2125kg/cm^2 for the first case and 2170kg/cm^2 for the second case just based on the measured data.

요　약

최근 현대 선박해양연구소 구조연구실에서 4,800대 적재 자동차 전용운반선 2척에 대하여 울산 미국간 각각 왕복 1항차에 걸쳐 실선계측을 수행하였다. 계측의 주요 목적은 자동차 운반선의 부분 횡격벽의 횡강도 검토 및 항해중 파랑하중에 대한 선체 응답의 연구등이다.

계측된 data를 가지고 단기 응답해석(short-term analysis)을 하였는데 항해중 선체에 발생하는 응력의 진폭의 분포는 대체로 Rayleigh 분포를 잘따르고 있었다. 그리고 횡격벽에서의 응력은 상갑판의 선측 방향 수평가속도와 밀접한 관계가 있는 것으로 나타났다.

접수일자 : 1988년 8월 6일, 재접수일자 : 1989년 11월 14일

* 정회원, 현대중공업(주) 선박해양연구소

단기 응답해석에서 얻어진 결과를 가지고 선박 운항시 발생 가능한 최대 응답치를 얻기위하여 장기 응답해석(long-term analysis)을 수행하였다. 해석결과중 본 계측 대상선의 Fr.132 부분 횡격벽의 응력집중 부분에서 10년 동안의 예측 최대응력은 약 2,150 kg/cm^{2}이었고 이 부분에 대한 예측 피로수명은 약 200일 이었는데 이 값은 실제 본선이 처녀해항후 crack손상을 입은 기간과 잘 일치하고 있다.

1. Introduction

Recently, Hyundai Heavy Industries Co., Ltd. has built many car carriers, in particular, large pure car carriers(PCC) owing to the latest increase of export of Hyundai cars to the United States of America. In general, pure car carrier has a special structural pattern in order to carry the cars as many as possible and to raise the efficiency of loading and unloading. In other words, the ratio of the draft to the depth is quite small and transverse bulkheads are arranged at rare intervals through the overall length. Moreover, the partial bulkhead structures are generally adopted above the free-board deck. Therefore, it has become generally known that the transverse strength of PCC is comparatively weak.

By the way, lately, it has been frequently reported that the transverse bulkhead structuctures of PCC, especially at the corner parts of partial bulkhead, were damaged by the crack in service. As a main reason for the damages, the racking deformation by the unsymmetric loading due to the ship motions during the voyage can be thought, but there are few data enough to examine the phenomena and to confirm the actual stress levels at the parts of concern in a sea-going condition.

In this situation, by the timely request of Hull Design Department of HHI, the Structure Department of Hyundai Maritime Research Institute has come to carry out the full-scale structural measurements of 4,800 unit pure car carriers "HYUNDAI NO.103" and "HYUNDAI NO.105", which were built in HHI Yard and ply regularly between Ulsan, Korea and U.S.A.

The main purpose of this measurement is to confirm the actual stress levels at the corner parts of partial bulkhead and to examine the ship's responses to the sea waves under way.

As a matter of fact, few helpful references have been presented about the full-scale measurement work in the country. At best are some papers relevant to the subject from NK, ABS, and other Classification Societies [5, 6]. Fortunately, even though it has not been long since our department started full-scale static and dynamic measurements, we have already experienced a few long-term full-scale measurements for some ships, for example, 254,000DWT large ore carrier "HYUNDAI GIANT" and 800 unit pure car carrier "HYUNDAI GEUM GANG" and so forth. Consequently, this long-term measurement work could be performed without considerable problems and measured data also seemed to be reasonable on the whole.

In this paper, are presented the procedures of this full-scale measurement and the results of short-term and long-term analyses for the measured data, in particularly, for the stresses at the corner parts of partial bulkhead.

2. FULL-SCALE MEASUREMENT

2.1. General

The subject ships used in this measurements are 4,800 unit pure car carriers "HYUNDAI NO.103" and "HYUNDAI NO.105", which were built in HHI Yard in 1986 and now ply mainly between Ulsan, Korea and the east coast of the United States of America. The principal dimensions of these two ships are as follows:

Length	B.P.	174.00m
Length	Scantling	173.63m
Breadth	MLD.	30.60m
Depth	(F'brd Dk) MLD.	14.21m

---

* Numbers [ ] refer to the references at the end of the paper.

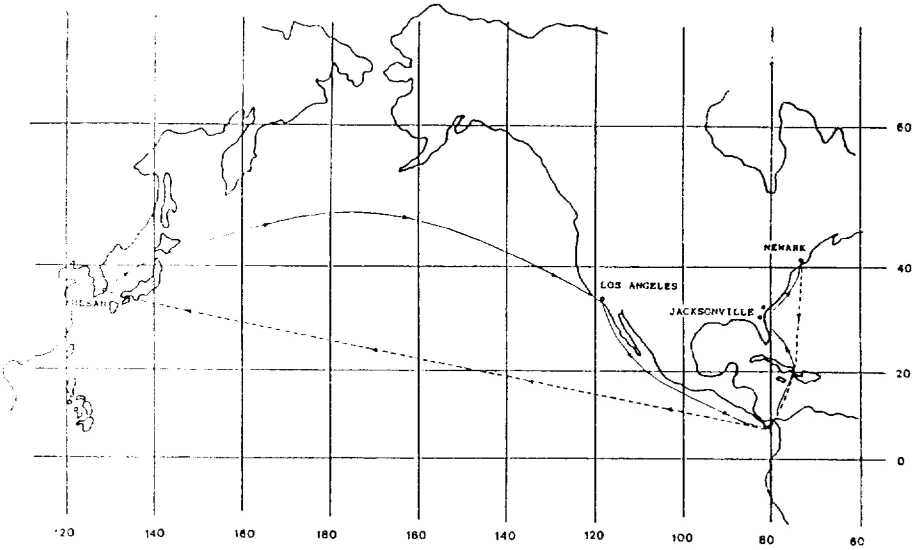


Fig. 2.1.1 General voyage route of subject ships

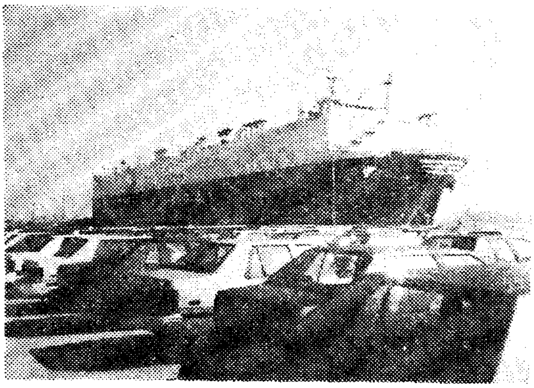
Depth	(Strength Dk) MLD.	29.67m
Draft	Designed	8.20m
Draft	Scantling	8.20m
C_b	at Scantling Draft	0.573

The 1st measurement was carried out for "HYUNDAI NO. 105" in a summer season from June 8, 1987 to July 28, 1987 for about 51 days. The voyage schedule was as follows:

Jun. 8~Jun.18	Ulsan→Los Angeles
Jun.20~Jun.25	Los Angeles→Panama Canal
Jun.27~Jun.29	Panama Canal→Jacksonville
Jul. 1~Jul. 2	Jacksonville→Newark
Jul. 4~Jul. 7	Newark→Panama Canal
Jul. 7~Jul. 28	Panama Canal→Ulsan

The 2nd measurement was performed for "HYUNDAI NO. 103", series ship of "HYUNDAI NO. 105", in a winter season from Feb. 12, 1988 to Apr. 9, 1988 for about 53 days. The measuring items and positions are almost same each other. The voyage schedule was as follows:

Feb. 12~Feb. 24	Ulsan→Los Angeles
Feb. 26~Mar. 3	Los Angeles→Panama Canal
Mar. 4~Mar. 7	Panama Canal→Jacksonville
Mar. 8	Jacksonville→Brunswick
Mar. 9~Mar.10	Brunswick→Newark
Mar.12~Mar.15	Newark→Panama Canal
Mar.19~Apr. 9	Panama Canal→Ulsan



Proto 2.1.1 Overall view of HYUNDAI NO. 105

The voyage route of the subject ships between Ulsan and U.S.A. is shown in Fig. 2.1.1, in which the full line represents the outward voyage route and the broken line represents the home voyage route. For reference, the overall view of "HYUNDAI NO. 105" is shown in Photo 2.1.1.

2.2. Measuring Equipments

The main measuring equipments used in this measurement are listed in Table 2.2.1. as follows: Besides the above listed equipments, a lot of auxiliary equipments and articles of consumption were used. The measuring equipments were arranged in the emergency generator room located amidship

Table 2.2.1 Measuring equipments

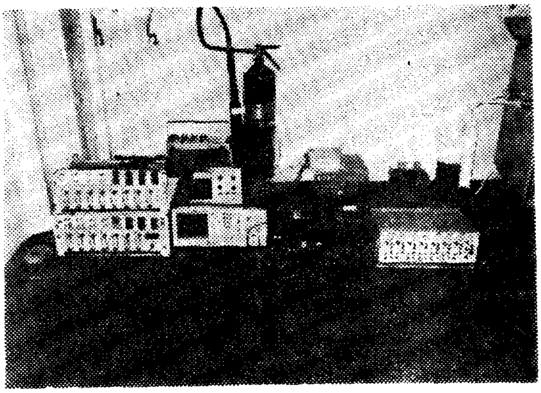
Equipments	Maker	Model No.
Conditioner	KYOWA	CDA-110A
Amplifier	EMI	SE1054
Pitch roll amp.	JAE	2000-101
Cassette data recorder	TEAC	XR-50
Tape recorder	EMI	SE7001A
Strain gage	KYOWA	KFW-5-Cl-11L100
Accelerometer	ENTRAN	KGS-500D
Vertical gyro	JAE	JG-2Y

on the upper deck as shown in Photo 2.2.1.

In a summer season or near the equatorial region, the temperature inside the emergency generator room was pretty high, but did not seem to have an effect on the measuring equipments.

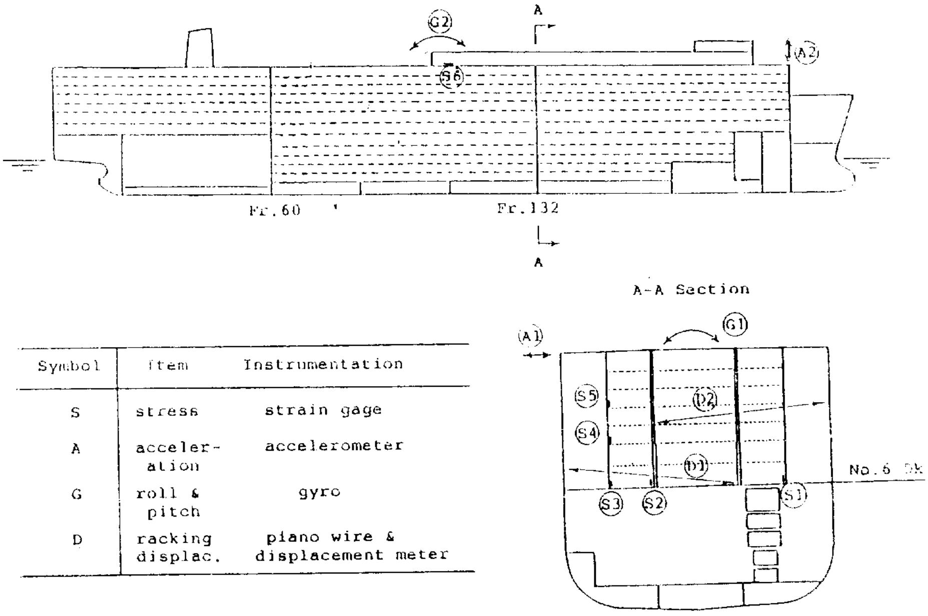
2.3. Measuring Items

The measuring items are local stresses at the corners of partial bulkhead, longitudinal stress at upper deck, pitch and roll acceleration, pitch and roll angle, racking deformation in No. 6 deck, and so forth.



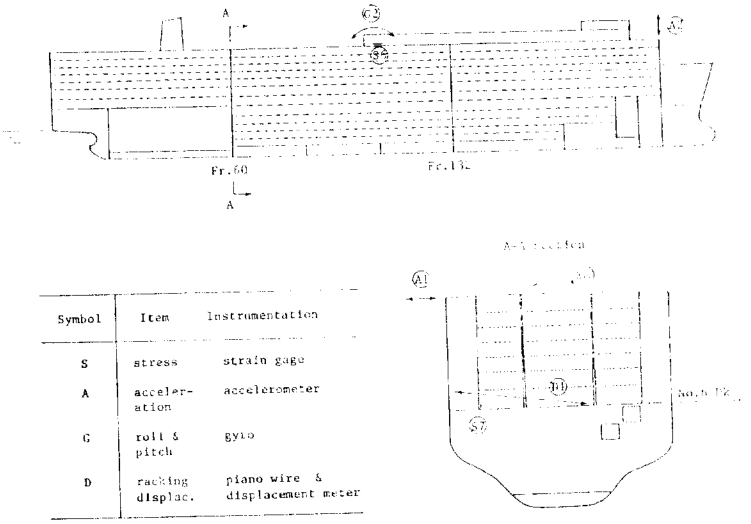
Proto 2.2.1 Measuring equipments

The measuring items and positions are shown in Fig. 2.3.1. for the 1st measurement and in Fig. 2.3.2. for the 2nd measurements. In the 2nd measurement, the port-side corner of partial bulkhead section(Fr. 132) in No. 6 deck got already damaged by the crack and starboard-side corner of this section had been reinforced by a small temporary bracket. And so, the local stress at the corner of partial bulkhead was measured at Fr. 60 engine room bulkhead section instead of at Fr. 132 BHD section



Symbol	Item	Instrumentation
S	stress	strain gage
A	acceler-ation	accelerometer
G	roll & pitch	gyro
D	racking displac.	piano wire & displacement meter

Fig. 2.3.1 Arrangement of measuring items and positions in the 1st measurement(HYUNDAI NO. 105)



Symbol	Item	Instrumentation
S	stress	strain gage
A	acceler-ation	accelerometer
G	roll & pitch	gyro
D	racking displac.	piano wire & displacement meter

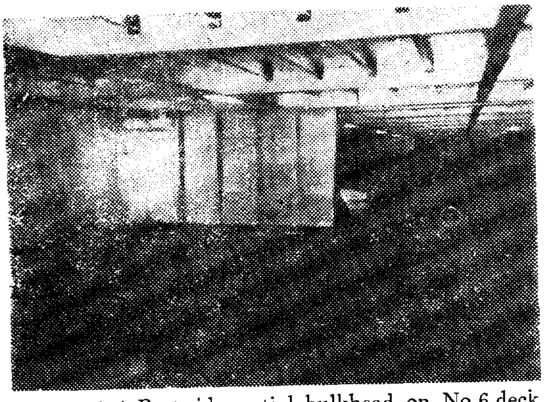
Fig. 2.3.2 Arrangement of measuring items and positions in the 2nd measurement(HYUNDAI NO. 103)

where local stresses were measured in the 1st measurement.

In Photo 2.3.1, the port-sied partial bulkhead on No. 6 deck is shown. At that corner, the subject ships were frequently damaged by the crack. Some measuring positions are shown in Photos 2.3.2 and 2.3.3.

For reference, the static stress measurement for the positions of S1~S5 in Fig. 2.3.1 was performed in the 1st measurement during total 4801 car loading at Ulsan. The obtained static stress levels were quite low, -20 to -130kg/cm^2.

Proto 2.3.2 Partial bulkhead corner on No. 6 deck at Fr. 132(S1 in Fig. 2.3.1)



Proto 2.3.1 Port-side partial bulkhead on No.6 deck

The data of weather and ship conditions such as wind speed and direction, Beaufort scale, temperature, atmospheric pressure, ship's speed, rpm of main engine were also recorded at every measuring time based on the Log Book recorded by the officers of subject ships. The measurement of racking deformation will be discussed in datail in Chapter 4.

2.4. Measuring Method

In the 1st measurement, the measurement has been regularly performed twice a day(08:00 and 20:00) for about 15 minutes. In the 2nd measurement, the measurement has been performed six times a day (00:00, 04:00, 08:00, 12:00, 16:00, and 20:00), and recording time was about 20 minutes. On home

Photo 2.3.3 Partial bulkhead corner on No.6 deck at Fr.60 (S7 in Fig. 2.3.2)

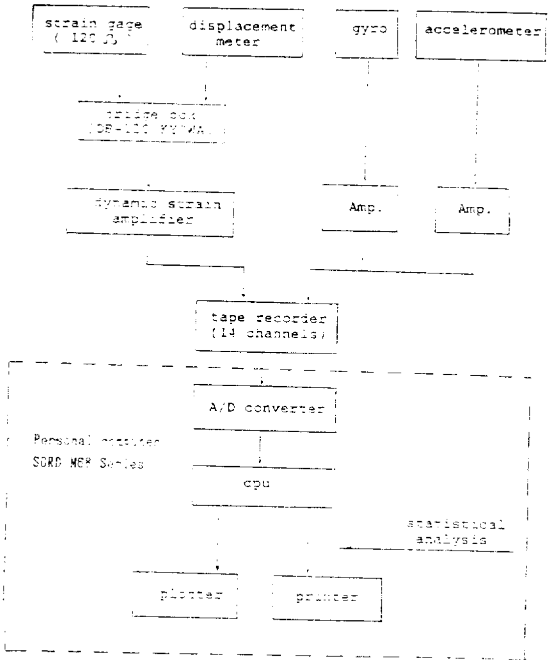


Fig. 2.4.1 Flow of measurement and analysis

voyages, i.e., in the ballast condition, the measurement was performed once a day 12:00 for the both cases. The flow of measuring procedure is shown in Fig. 2.4.1.

3. Analysis of Measured Data

3.1. General

The distribution of Beaufort wind scale that the subject ships have met during the voyage between Ulsan and Newark, U.S.A. are shown in Fig. 3.1.1, from which it can be known that the sea state during the 2nd measurement, i.e., in a winter season, was a little severer than that during the 1st measurement.

Some examples of measured signals during 5 minutes are shown in Fig. 3.1.2 and Fig. 3.1.3 for each measuring items. From the signals in these figures, it can be guessed that the local stress at the section of transverse bulkhead has a very close relation with the rolling, and the longitudinal stress at upper deck has somewhat a relation with the pitching.

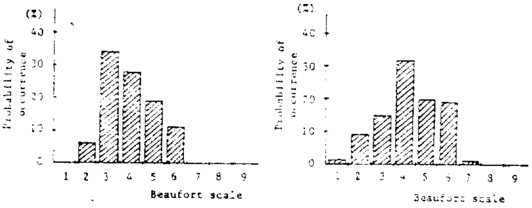
In this analysis, mainly the local stresses at the corners of partial bulkhead have been analysed since those are the main concern in the strength of pure car carrier. The short-term frequency analysis for the stress amplitude has been performed with the measured stress signals.

For the frequency analysis of stress amplitude, the mean crossing range (peak to peak) count method has been adopted, in which double stress amplitude adopts the upper maximum value and the lower minimum value crossing the line of the mean value of wave form as shown in Fig. 3.1.4.

Finally, based on the results of short-term analysis, the long-term analysis has been attempted in order to estimate the maximum probable value for the considering period.

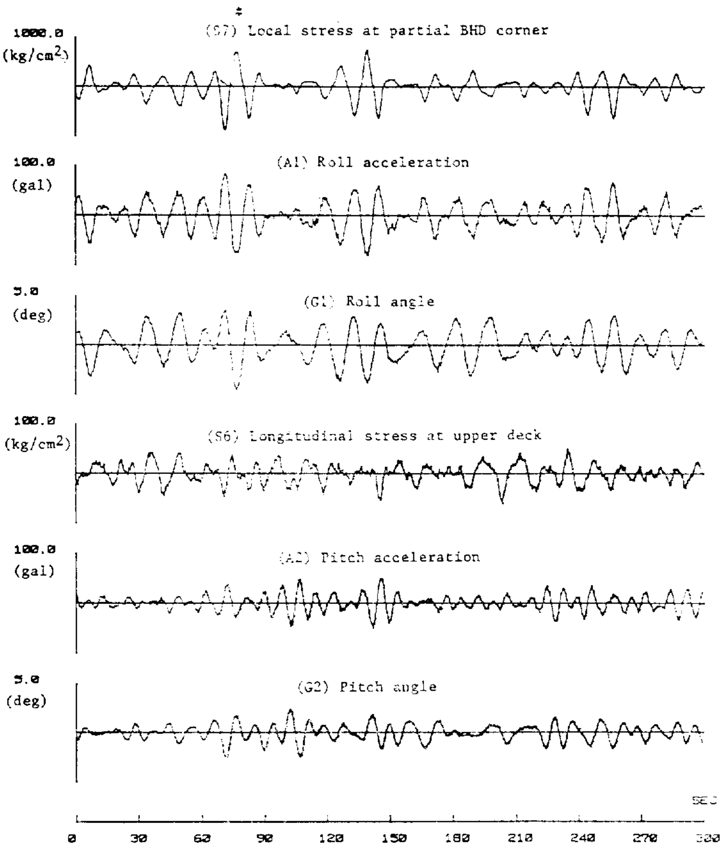
3.2. Short-term Analysis

It is of common knowledge that the wave-induced stresses and motions of ships are distributed according to the Rayleigh distribution, provided the sea state, ship speed, and heading remain steady throughout the period under consideration [3]. This period of



(a) 1st Measurement (summer) (b) 2nd Measurement (winter)

Fig. 3.1.1 Distribution of Beaufort wind scale during the measurement



* Refer to Fig. 2.3.2

Fig. 3.1.2 Examples of measured signals in the 2nd measurement (Feb. 17, 1988, beaufort scale 5, full load)

steady conditions is called “short-term”. The Rayleigh distribution is defined with one parameter E as follows:

$$p(x)=\frac{2x}{E}\cdot\exp(-x^2/E),\quad x\geqq 0 \qquad (3.2.1)$$

where $p(x)$ is the probability density function of x, and

E is the mean value of the squares of x.

Thus the cumulative probability distribution function of the Rayleigh distribution is represented as follows:

$$P(x)=\int_{-\infty}^{x}p(x)dx=1-\exp(-x^2/E)$$

$$=1-\exp(-v^2) \qquad (3.2.2)$$

where $v(=x/\sqrt{E})$ is the standardized variate.

A typical example of the Rayleigh distribution is shown in Fig. 3.2.1 for the stress amplitudes of local stress measured at the port-side corner of Fr. 60 partial bulkhead of the subject ship in the 2nd measurement.

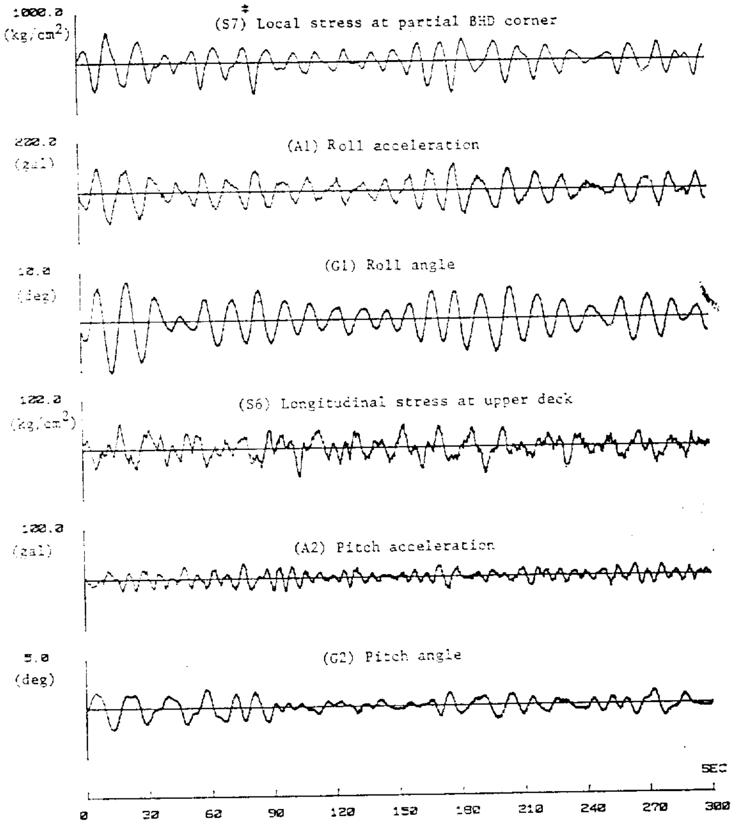
The measured analog signals have been converted through the A/D converter into the digital values with the sampling interval of 0.5 sec. and then the frequency analysis for the stress amplitudes has been performed by the fore-mentioned ‘mean crossing range (peak to peak) count method’. And the mean square value of stress amplitudes E is calculated by the following formula.

$$E=\frac{1}{N}\sum_{i=1}^{N}\sigma_i^2 \qquad (3.2.3)$$

where N is the number of amplitudes, and

σ_i is the stress amplitude.

The theoretical line of Rayleigh distribution according to the mean square value E calculated from the measured stress amplitudes by the above formula



‡ Refer to Fig. 2.3.2

Fig. 3.1.3 Examples of measured signals in the 2nd measurement (Apr. 8, 1988, beaufort scale 4, ballast)

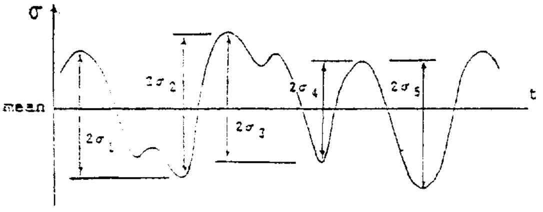


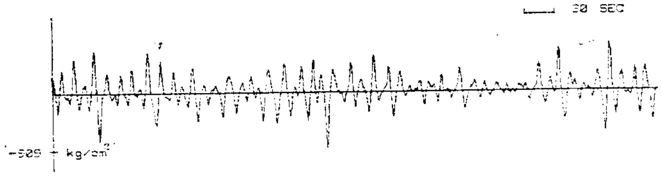
Fig. 3.1.4 Mean crossing range count(peak to peak)

is also drawn in Fig. 3.2.1, which shows fairly good agreement between the measured data and the theoretical Rayleigh distribution.

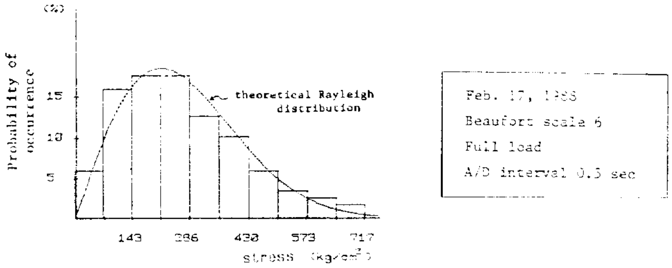
Let us examine the confidence of assumption that the obtained wave-induced stresses follow the Rayleigh distribution. For this purpose, the measured data presented in Fig. 3.2.1 have been plotted on the probability paper of Rayleigh cumulative distribution and the results are shown in Fig. 3.2.2, in which all the measured data fall between the 90% confidence limit lines. For reference, it can be said that the measured data follow well the Rayleigh distribution if the more than 90% of measured data fall between the 90% confidence limit lines [3].

Longuet-Higgins [3] shows that the largest probable value $x_{\max}$ out of N measurements becomes approximately $\sqrt{E}\cdot\sqrt{\log_e N}$ for large N. And so, it is of interest to compare this value with the measured largest value. For the case in Fig. 3.2.2, the most probable value of maximum stress amplitude is 663 ($306\sqrt{\log_e 110}$) kg/cm² and the measured maximum one is 717kg/cm², which shows a good agreement with each other.

The relation between Beaufort wind scale and the maximum value of stress amplitude at partial BHD



(a) Time history of measured stress



(b) Distribution of stress amplitude

Fig. 3.2.1 Measured stress signals and distribution of stress amplitude

corners for every measurement is graphically shown in Fig. 3.2.3 and Fig. 3.2.4, which show a comparatively large scatterness for both cases. Therefore, it is very hard to say that Beaufort scale and the maximum stress amplitude have a certain relation. However, the maximum values for each Beaufort scale seem to have some tendency.

It is of interest to look into the correlation between the ship responses, for example, transverse local stress at BHD section and rolling acceleration, longitudinal stress and pitching acceleration at fore-end. Among the measured data obtained in the 2nd measurement, the selected maximum amplitudes of the transverse local stress and the rolling acceleration are plotted in Fig. 3.2.5, which shows a good linearity, and the correlation coefficient is 0.942. In Fig. 3.2.6, the correlation between the longitudinal stress and the pitching acceleration are shown graphically and its correlation coefficient is 0.645.

3.3. Long-term analysis

It is the main purpose of this section to estimate the maximum probable value of wave-induced stress amplitude at the corners of partial bulkhead of subject ship, i.e., the main parts of concern based on the results of short-term analysis. For this purpose, two statistical distributions have been used in this analysis and the obtained results are described as follows:

1) Exponential distribution

It is assumed that the cumulative distribution of cycles of stress amplitude for a long-term distribution can be represented by the following exponential form [5].

$$N=a\cdot 10^{-bx} \text{ or } \log N=-bx+\log a \qquad (3.3.1)$$

where N is cycles per unit interval,

x is stress amplitude, and

a and b are constants.

The constants 'a' and 'b' can be graphically obtained as shown in Fig. 3.3.1. With the given data (x_1, $\log N_1$), (x_2, $\log N_2$), $\cdots$, (x_n, $\log N_n$), the following linear equation can be derived by the least square method [2].

$$\log N=\beta\cdot x+\alpha \qquad (3.3.2)$$

where $\beta=\dfrac{n\sum(x_i\cdot\log N_i)-\sum x_i\cdot\sum\log N_i}{n\sum(x_i)^2-(\sum x_i)^2}$

$$\alpha=\frac{\sum(x_i)^2\cdot\sum\log N_i-\sum x_i\cdot\sum(x_i\cdot\log N_i)}{n\sum(x_i)^2-(\sum x_i)^2}$$

Therefore, constants 'a' and 'b' can be obtained from Eq. 3.3.1 and Eq. 3.3.2.

$b=-\beta$

$a=10^{\alpha}$

And the maximum probable value for the measuring period is $(\log a)/b$. The maximum value for a longer period is to be obtained just by multiplying an extension factor.

Results of long-term analysis by this method for

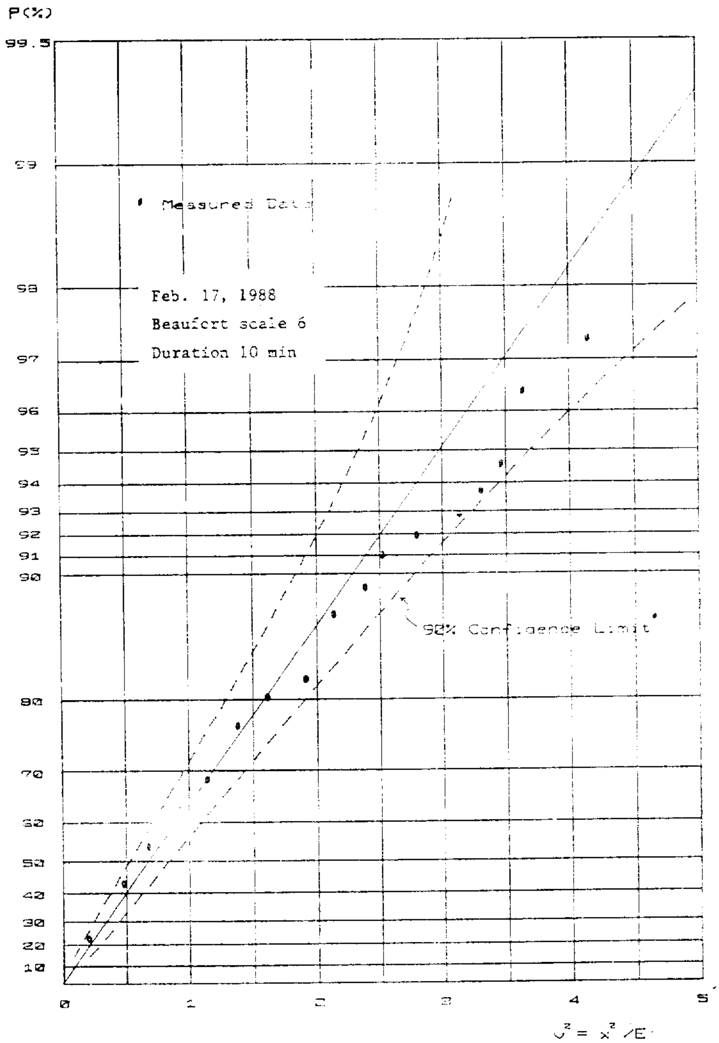


Fig. 3.2.2 Rayleigh cumulative distribution of stress amplitude at partial BHD corner (S7), (refer to Fig. 3.2.1)

the local stresses at the partial bulkhead corners of subject ships are graphically represented in Fig, 3.3.2 and Fig. 3.3.3. In Fig. 3.3.2, the long-term distribution of stress amplitudes is shown for the stresses measured at the port-side corner of Fr. 132 partial bulkhead in the 1st measurment. The full line in the figure represents the distribution of measured data for 51 days.

In the 1st measurement, recording has been performed twice a day for 15 minutes and the analysis of measured data for 10 minutes every measurement. Therefore, it has been assumed that the analysed data for 10 minutes are representative of data for 12 hours. The measured data and the assumed linear line are in good agreement with each other. The dashed line means the assumed distribution for 10 years obtained by multiplting the factor 10·365/51 to the above distribution. The calculated maximum probable value of stress amplitude for 10 years is 2125kg/cm^2 just based on this data.

In Fig. 3.3.3, the results for the stresses measured at the port-side corner of Fr. 60 partial bulkhead in the 2nd measurement are shown. The assumed linear distribution also agree well with the measured data.

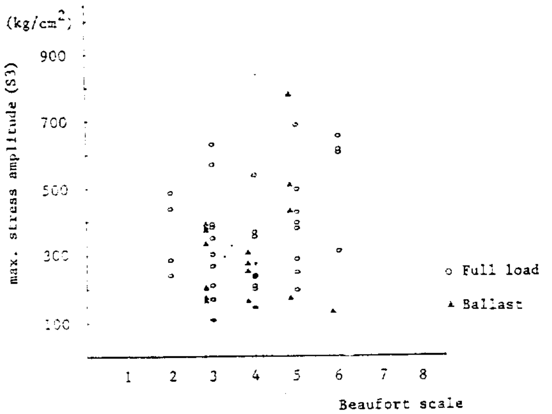


Fig. 3.2.3 Relation between max. stress amplitude and beaufort scale in the 1st measurement

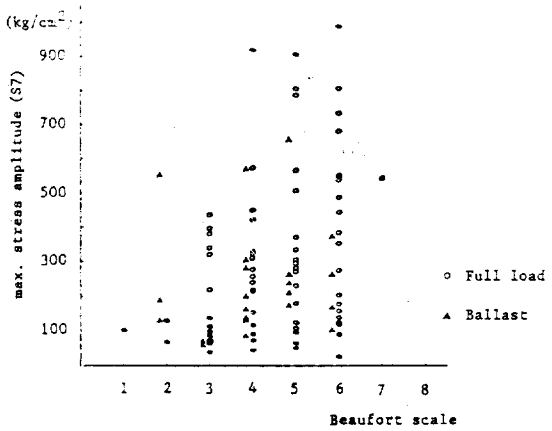


Fig. 3.2.4 Relation between max. stress amplitude and beaufort scale in the 2nd measurement

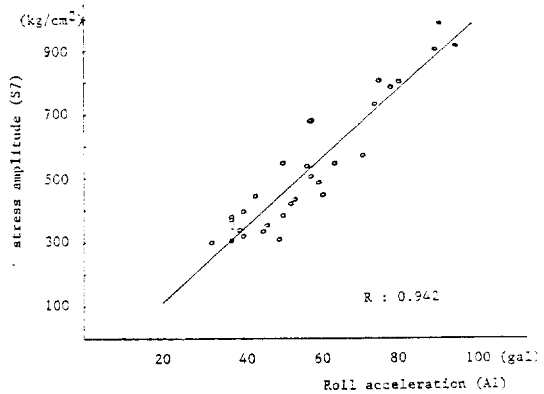


Fig. 3.2.5 Correlation between local stress at partial BHD corner and roll acceleration

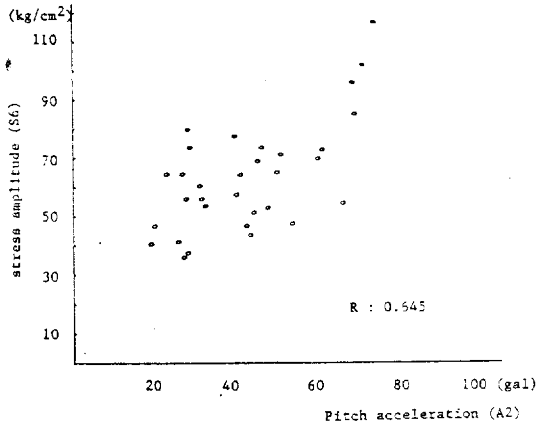


Fig. 3.2.6 Correlation between longitudinal stress at upper deck and pitch acceleration

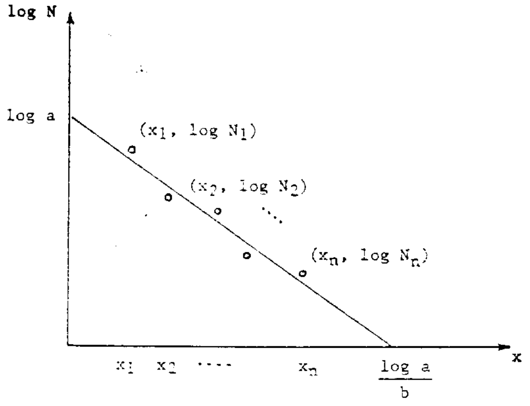


Fig. 3.3.1 Exponential distribution of stress amplitude

The full line also represents the distribution of measured data for 53 days. In the 2nd measurement, recording has been performed six times a day for 20 minutes and the analysis of measured data for 15 minutes every measurement. Therefore, it has been assumed that the analysed data for 15 minutes are representative of data for 4 hours. The dashed line means the assumed distribution for 10 years obtained by multiplying the factor 10·365/53 to the above distribution. The maximum probable value of stress amplitude for 10 years is $1485 kg/cm^2$ just based on the measured data during the 2nd measurement.

With the given data of Fig. 3.3.2 and Fig. 3.3.3, the fatigue life at the considering parts has been

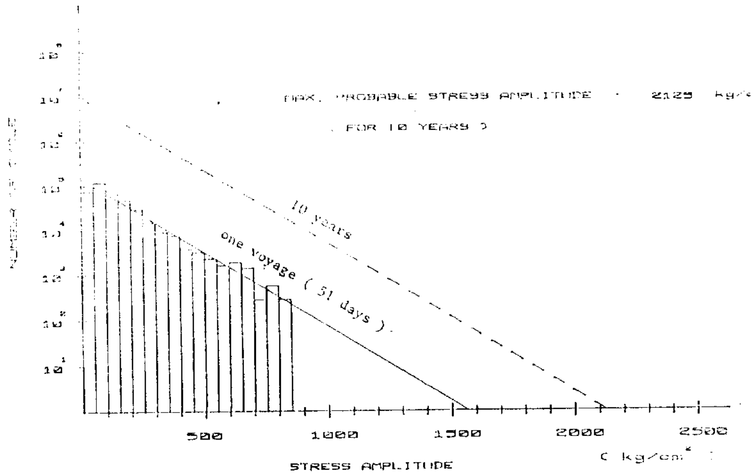


Fig. 3.3.2 Long-term distribution of stress amplitude at partial BHD corner in the 1st measurement (point S3 in Fig. 2.3.1)

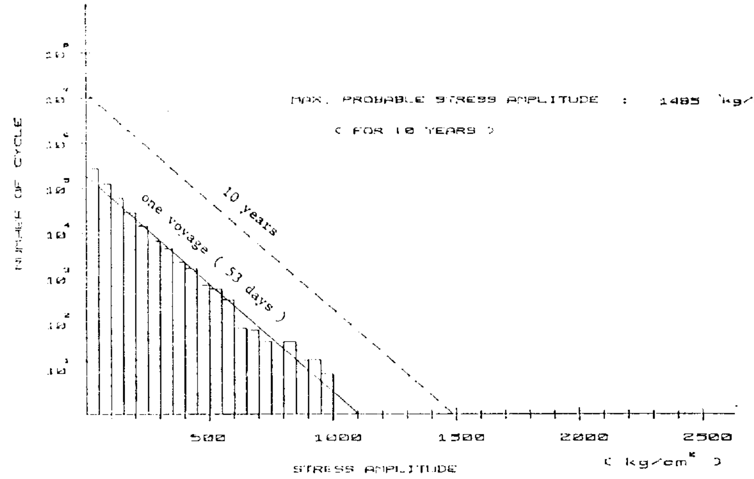


Fig. 3.3.3 Long-term distribution of stress amplitude at partial BHD corner in the 2nd measurement (point S7 in Fig. 2.3.2)

estimated based on the assumption of linear cumulative damage rule (Miner-Palmgren rule), in which cumulative damage ratio is obtained by the following formula. The S-N curve used in this calculation is Type "W" Curve among the curves presented in DNV Note [7].

$$D=\sum_{i=1}^{k}\frac{n_i}{N_i} \tag{3.3.1}$$

where D is damage ratio,

k is the number of stress blocks,

n_i is the number of stress cycles in stress block i, and

N_i is the number of cycles to failure at constant stress range σ_i.

The obtained damage ratio for the case of Fig. 3.3.2 is 0.256 for 51 days. Therefore, the estimated fatigue life is about 199 days (51/0.256). Actually, the subject ships got damaged at that point on her maiden or 2nd voyage, that is, after approximately 50 or 100 day service. In case of Fig. 3.3.3, the damage ratio is 0.073 for 53 days and the estimated fatigue life is 2.0 years(53/0.073/365). For reference, it has been not reported until now that the crack occurred at this point.

2) Double exponential distribution

It is assumed that the extreme values of stress amplitude obtained in each short-term analysis are approximated by a double exponential distribution [1]. It has been suggested by Gumbel that, if an underling distribution of population like the Rayleigh distribution has an exponentially decaying tail in the direction of the extreme, the cumulative distribution function of largest values in repeated large samples from this distribution converges asymptotically to the following double exponentially limiting form (Gumbel's Type I limiting form).

$$F(x)=\exp[-\exp(-An(x-Un))] \text{ or}$$
$$F(s)=\exp[-\exp(-s)] \qquad (3.3.3)$$

where An, Un are constants and

s is the reduced variate $(=An(x-Un))$.

Based on the extreme values obtained from the short-term analysis, the above contants 'An' and 'Un' can be graphically estimated. N extreme values from a population of the exponential type are plotted on a double exponential extremal probalility paper, such that the ith value is plotted at the probability $i/(N+1)$ when they are arranged in order of increasing magnitude. If the results show a linear trend with a positive slope, constants 'An' and 'Un' can be estimated approximately by graphically drawing a straight line $(s=An(x-Un))$ through the plotted data points by the least square method.

The most probable maximum value can be calculated by the following formula:

$$F(x_{\max})=1-\frac{1}{n} \qquad (3.3.4)$$

where $x_{\max}$ is the most probable maximum value and

n is the number of extreme values during the considering period.

The results of long-term analysis by this meathod are shown in Fig. 3.3.4 to Fig. 3.3.5. In Fig. 3.3.4, the extreme values of stress amplitude obtained in each short-term analysis for the stresses measured during 46 days at the port-side corner of Fr. 132 partial bulkhead in the 1st measurement are plotted in the extremal probability paper. The extreme values used in Fig. 3.3.4 are the estimated largest values of stress amplitude corresponding to the duration of 12 hours and have been calculated by the formula $\sqrt{E}\cdot\sqrt{\log_e(12\cdot 60/10\cdot N)}$, which is the largest probable value estimated with $12\cdot 60/10\cdot N$ measurements in case that the underlying distribution of population follows the Rayleigh one, where E is the mean square of stress amplitudes obtained in short-term

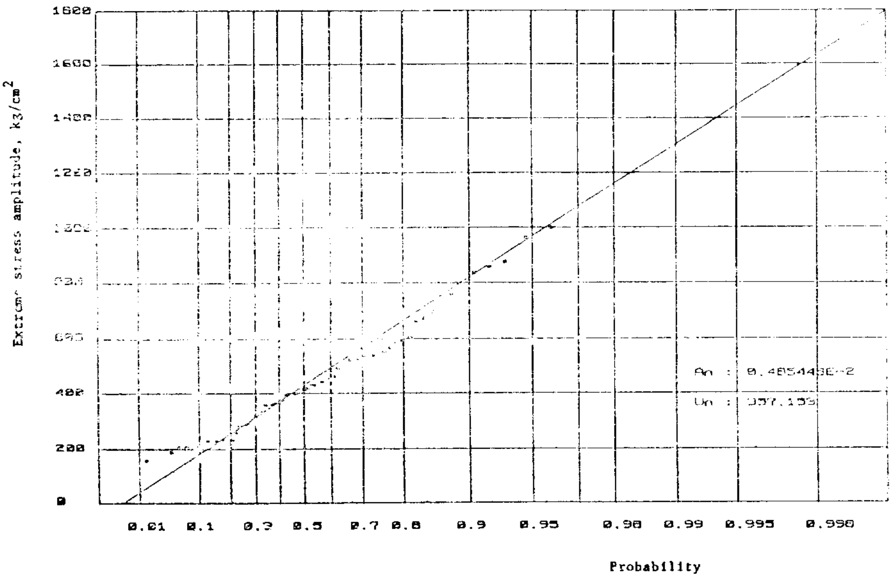


Fig. 3.3.4 Long-term distribution of extreme values of stress amplitude at partial BHD corner in the 1st measurement (point S3 in Fig. 2.3.1)

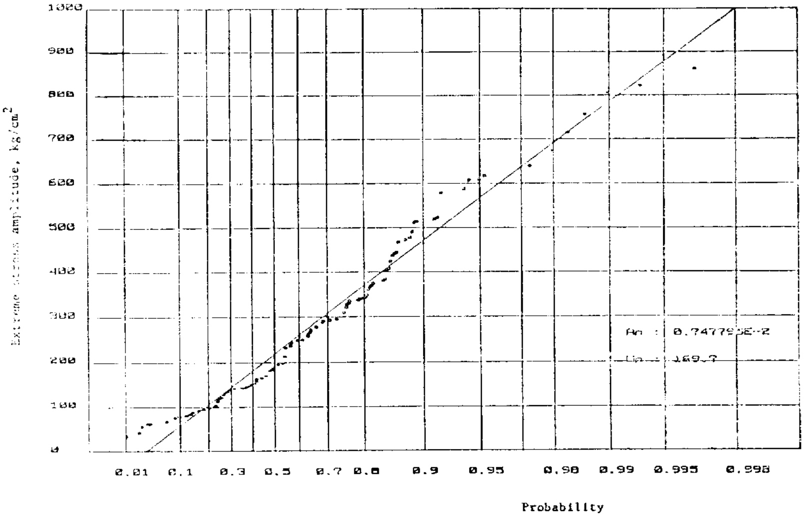


Fig. 3.3.5 Long-term distribution of extreme values of stress amplitude at partial BHD corner in the 2nd measurement (point S7 in Fig. 2.3.2)

analysis for 10 minutes and N is the number of stress amplitudes for 10 minutes. The results show a good double exponential distribution. As shown in Fig. 3.3.4, the calculated values of 'An' and 'Un' are 0.00485 and 357. And the subject ship has been under way for 46 days out of 51 days in the 1st measurement. Therefore, from Eq. 3.3.4, the maximum probable value for 10 years may be estimated as follows:

$$x_{\max}=-\frac{1}{An}\log_e\left(-\log_e\left(1-\frac{1}{n}\right)\right)+Un$$

$$=-\frac{1}{0.00485}\log_e\left(-\log_e\left(1-\frac{51}{2\times365\times10\times46}\right)\right)+357$$

$$=\underline{2170\text{kg/cm}^2}$$

In Fig. 3.3.5, the extreme values of stress amplitude for the stresses measured during 48 days at the port-side corner of Fr. 60 partial bulkhead in the 2nd measurement are also plotted in the extremal probability paper. The extreme values used in Fig. 3.3.5 are the estimated largest values of stress amplitude corresponding to the duration of 4 hours and have been calculated by the formula $\sqrt{E}\cdot\sqrt{\log_e(4\cdot60/15\cdot N)}$, which is the largest probable value estimated with $4\cdot60/15\cdot N$ measurements, where E is the mean square of stress amplitudes obtained in short-term analysis for 15 minutes and N is the number of stress amplitudes for 15 minutes. As shown in Fig. 3.3.5, the calculated values of '*An*' and '*Un*' are 0.00748 and 170. And the subject ship has been under way for 48 days out of 53 days in the 2nd measurement. Therefore, the maximum probable value for 10 years may be estimated as

Table 3.3.1 Summary of long-term analysis

Items	1st measurement	2nd measurement
position	Fr. 132 port-side partial BHD corner	Fr. 60 port-side partial BHD corner
measuring duration	51days	53days
probable max. stress amplitude for measuring duration	1,560kg/cm^2	1,100kg/cm^2
probable max. stress amplitude for 10 years by		
1) exponential distribution	2,125kg/cm^2	1,485kg/cm^2
2) double exp. distribution	2,170kg/cm^2	1,493kg/cm^2
estimated fatigue life	199days	2years

follows:

$$x_{\max} = -\frac{1}{0.00748}\log_e\left(-\log_e\left(1-\frac{53}{6\times365\times10\times48}\right)\right)$$
$$+170$$
$$=\underline{1493\text{kg/cm}^2}$$

The obtaind results of long-term analysis are summarized in Table 3.3.1.

4. Discussions and Conclusions

In general, the sea state of the North Pacific is much severer in winter than in summer. Following example shows this fact well. The distributions of significant wave height at Area 20 in the North Pacific (area defined in 'Global Wave Statistics,' BMT) are shown in Fig. 4.1 for summer and winter seasons, from which it can be known that considerably big waves happen quite often in winter season.

However, as shown in Fig. 3.1.1, the sea state that the subject ship "HYUNDAI No. 103" has encountered on her voyage route in the 2nd measurement has been fairly moderate despite of winter season. The maximum Beaufort wind scale at that time was 7 at most. But during other voyage of last winter the subject ship has ever experienced the sea state of Beaufort scale 10. Therefore, it may be thought that the estimated maximum stress amplitude at Fr. 60 partial BHD corner from the 2nd measurement is more or less lower as compared with the actual maximum probable value.

The voyage route of subject ships, "HYUNDAI NO. 103" and "HYUNDAI NO. 105," 4800 unit pure car carriers, is almost the same as the route shown in Fig. 2.1.1 even though the master occasionally changes the course to some degree in order to avoid the low atmospheric pressure, which in general accompanies the very severe sea state. But, this time there were no situations like that.

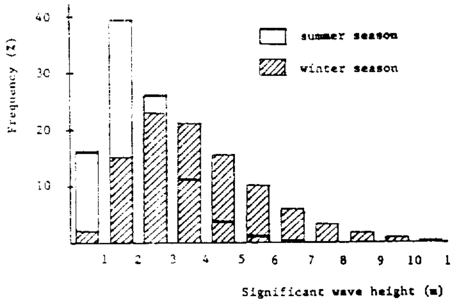


Fig. 4.1 Distributions of significant wave height at Area 20 in the North Pacific

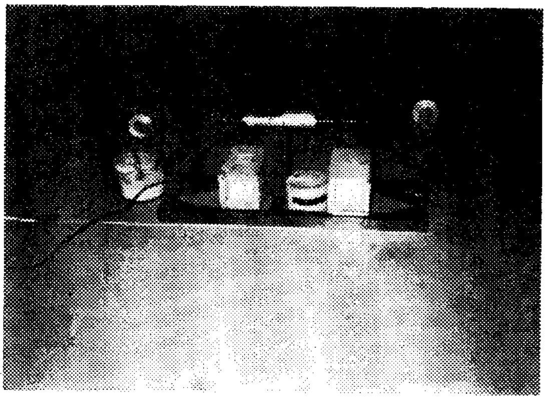


Photo 4.2 Racking deformation measuring equipment used in the 1st measurement

In general, the transverse strength of pure acr carrier is comparatively weak. The structural damage actually often happens to the part of stress concentration in the transverse bulkhead structures. Therefore, in this measurement, we have focused our attention to the measurement and analysis of local stresses at the corners of partial bulkhead above the free-board deck. Besides, roll and pitch acceleration, roll and pitch angle, longitudinal stress at upper deck, and racking deformation at Fr. 132 BHD section have been measured together. Among these measuring items, the racking deformation has been measured on No. 6 deck as shown in Fig. 2.3.1 using the piano wire, the linear displacement transducer and the measuring apparatus. In the 1st measurement, the 8kg weight has been used to strain the piano wire as shown in Photo 4.1. By the way, the measured signals were very fluctuating and did not coincide with the rolling signals.

In the 2nd measurement, the spring instead of weight has been used as shown in Fig. 4.2. This time there were almost no variations of signals of racking deformation. Therefore, it can be thought that the fluctuations of signals in the 1st measurement was not due to the racking deformation but due to

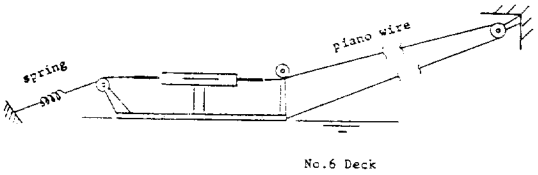


Fig. 4.2 Racking deformation measuring equipment used in the 2nd measurement

the inertia of the weight by the ship motion. And it seems to be difficult to obtain the signals of racking deformation just within one hold.

As a matter of fact, it has been a long time since LR, DNV, NK, and other Classification Societies and companies concerned started the full-scale measurement of ships. Moreover, it seems that they have already finished or reached the final stage in developing the hull strength monitoring system, which is an application of full-scale measuring system and can be established over a long time with much experience of full-scale measurements.

By the way, the Structure Department of HMRI started the full-scale measurements of ships at most about 1 year ago and the experience accumulated during that time is trifling, and now the automatic measuring system has not been established yet, which is absolutely needed for a long-term measurement.

However, we are now planning the supplement of measuring equipments and the establishment of automatic measuring and analysis system. And then, with this more developed measuring equipments and system, the Structure Department of HMRI will continue to carry out this kind of full-scale measurement. And now, the measurements of bulk carrier or container ship are under consideration with special concern to the longituinal strength in service.

The main conclusions and results obtained in this measurement can be summarized as follows:

1) One of the major objectives of this project is the confirmation of our capability and feasibility for the full-scale measurement of ships and other ocean structures. Even though the results of this measurement do not give a decisive aid to the design of car carrier, this full-scale measuring project may have resulted in success.
2) It has been confirmed that the short-term distributions of wave-induced stresses follow on the whole the Rayleigh distribution.
3) There is a close correlation between the transverse local stress at BHD section and the roll acceleration. The calculated correlation coefficient between the maximum stress amplitudes at Fr. 60 partial BHD corner and the maximum amplitudes of roll acceleration is 0.942 based on the data measured in the 2nd measurement.
4) Actually, fairly high stresses occurred at the corners of partial bulkhead. The estimated fatigue life at Fr. 132 partial BHD corner just based on the measured data in the 1st measurement is 199 days. For reference, the subject ships actually got damaged there by the crack on their maiden or 2nd voyage.
5) Based on the results of short-term analysis, the long-term analysis for the stresses measured at partial BHD corners has been performed by two methods, as described in Section 3.3, mainly in order to obtain the maximum probable value of stress amplitude. The results by both methods agree well with each other. The maximum stress amplitude at Fr. 132 partial BHD corner estimated from the data measured in the 1st measurement is about 2150kg/cm^2.

5. Acknowledgement

The co-operation of Ulsan office of HYUNDAI MERCHANT MARINE COMPANY, especially of Manager Seong S. Chung and Mr. Cheol S. Lee, is gratefully acknowledged. Also, the co-operative assistance of the captain Jong M. Kim, the captain Seong N. Kim, many officers, and crew of "HYUNDAI NO.105" and "HYUNDAI NO.103" made possible this long-term measurement work. Finally, the authors would like to thank Dr. Yoon H. Kim, Director of HMRI and Mr. Chi H. Inn, Director of Hull Design Dep't, who gave us an encouragement and a special concern for this full-scale measurement of ships.

References

〔1〕 Alfredo H-S. Ang and Wilson H. Tang, "Probability Concepts in Engineering Planning and Design", John Wiley & Sons (1984).

〔2〕 John E. Freund, Mathematical Statistics, Prentice Hall (1962).

〔3〕 N.H. Jasper, "Statiatical distribution Patterns of Ocean Waves and of Wave-Induced Ship Stresses and Motions with Engineering Applications", SNAME (1956).

〔4〕 Oi Hi. Kim, Jin S. Park and Jae K. Chung, "Full-Scale Structural Measurements of Pure Car Carrier", Hyundai Maritime Research Institute Report No. (SD) 88012 (1988).

〔5〕 Akira Nitta and Michifumi Yuasa, "Full-Scale Measurements and Stress Analysis on the Transverse Strength of Car Carriers" *Journal of Society of Naval Architects of Japan*, Vol. 147 (1980).

〔6〕 Michifumi Yuasa, Kohei Suzuki, and Yutaka Tatara, "On Hull Response of Ships in Service (1st Report: Hull Response of a Pure Car Car Carrier)", *Journal of the Society of Naval Architects of Japan*, Vol. 159 (1986).

〔7〕 Det Norske Veritas, "Fatigue Strength Analysis for Mobile Offshore Units", Classification Notes, Note No. 30 2 (1984).