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A parametric study based on spectral fatigue analysis for 170k LNGC

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ABSTRACT: *The Spectral Fatigue Analysis is representative fatigue life assessment method for vessels. This Analysis is performed generally for the whole vessel and many assessment sites. The spectral fatigue analysis is performed through the process of hydrodynamic response analysis, global structural analysis, local structural analysis and calculation of fatigue damage. In these processes, fatigue damage is affected by many variables. The representative variables are S-N curve data, wave scatter data, wave spectrum, bandwidth effect and etc. In this paper, the effects of these variables to the fatigue damage are analyzed through the spectral fatigue analysis for 170k LNGC.*

KEY WORDS: Spectral Fatigue Analysis; Fatigue Life Prediction; Parametric Study; Design Variable.

NOMENCLATURE

N	fatigue life
$\log \overline{a}$	intercept of the $\log N$ axis
m	inverse negative slope of the S-N curve
S_η	wave energy spectrum
H_s	significant wave height
T_z	zero-crossing period
ω	wave frequency
ω_p	peak wave frequency
ε	bandwidth parameter
m_n	moment of spectrum

INTRODUCTION

The fatigue fracture is a primary cause of the fracture of offshore structures and vessels. The fatigue fracture is a phenomenon which is occurred by cumulative damage due to fluctuating loads. The fatigue life is composed with the fatigue crack initiation life and fatigue crack propagation life. The fatigue life of vessels is assessed by using Miner's linear cumulative law(Miner, 1945).

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The representative fatigue life assessment methods are simplified fatigue life assessment method and spectral fatigue life assessment method. (DNV, 2008; ABS, 2006; Lloyd, 2002; KR, 2010) In the case of simplified fatigue life assessment method, the dominant loads which determine the stress range of the assessment sites are calculated by empirical formulas. The specific characteristic of the simplified method is assumption of the long-term distribution of stress ranges. The long-term distributions are assumed by using Weibull distribution. Because of this assumption, we could not consider the effect of variables which affect the long-term distribution of the stress ranges in the simplified method.

The spectral fatigue analysis method is used for fatigue life assessment for vessels generally. In the case of spectral fatigue analysis, the motion RAO about unit amplitude waves for specific heading angle and wave frequency are calculated and load transfer function is calculated by using the motion RAO. Then, the global structural analysis using load transfer function and global FE model is performed. The result of global structural analysis provides boundary displacements of local FE model. The next step is calculation of stress transfer function at the hot spot and final fatigue damage using this stress transfer function, wave energy spectrum, wave scatter data and S-N curve. In the process of the spectral fatigue analysis, the fatigue damage is affected by several variables like S-N curve, wave scatter data, wave spectrum, bandwidth effect and etc. In this paper, through the spectral fatigue analysis for 170k LNGC, the effects of these variables to the fatigue damage are analyzed.

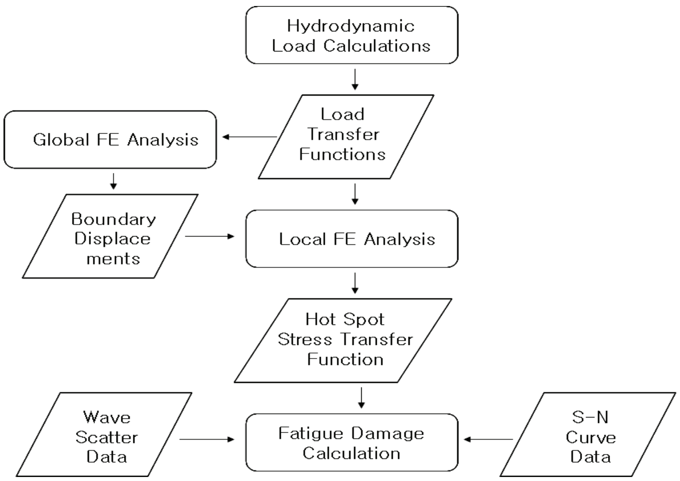

Fig. 1 Flowchart of Spectral Fatigue Analysis.

DESIGN VARIABLES

S-N curve

S-N curve is necessary data when we assess fatigue life of structure by using Miner's linear cumulative law. The S-N curve is based on experimental results and different for the each material. The S-N curves used in fatigue life assessment of hull structures are generally suggested by classification societies. The representative S-N curves are ABS S-N curve and DNV S-N curve. Their S-N curves are as follows.

$$\log N = \log \bar{a} - m \log \Delta\sigma \quad (1)$$

Table 1 ABS S-N Curve.

Class	$N \le 10^7$		$N > 10^7$	
	$\log \bar{a}$	m	$\log \bar{a}$	m
B	15.006	4	19.009	6
C	13.626	3.5	17.412	5.5
D	12.182	3	15.627	5
E	12.015	3	15.362	5
F	11.800	3	14.999	5
F2	11.634	3	14.722	5
G	11.394	3	14.330	5
W	11.197	3	14.007	5

Table 2 DNV S-N Curve.

Class	$N \le 10^7$		$N > 10^7$	
	$\log \bar{a}$	m	$\log \bar{a}$	m
I	12.164	3	15.606	5
III	15.117	4	17.146	5
IV	12.436	3	12.436	3

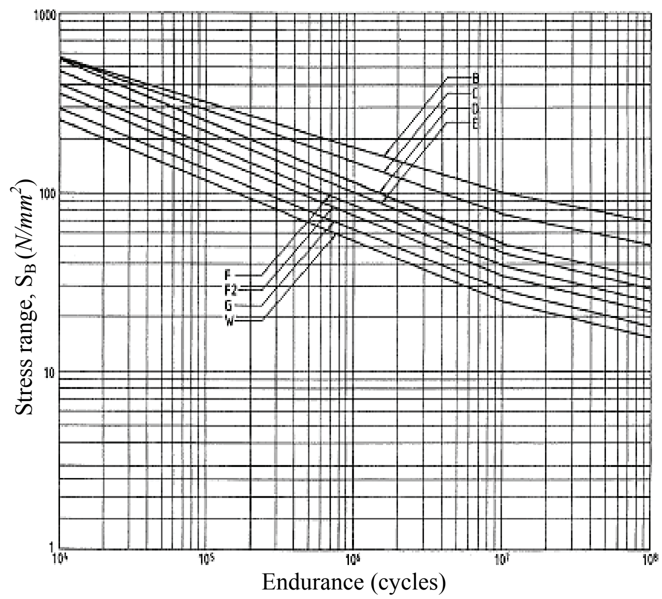

Fig. 2 ABS S-N Curve.

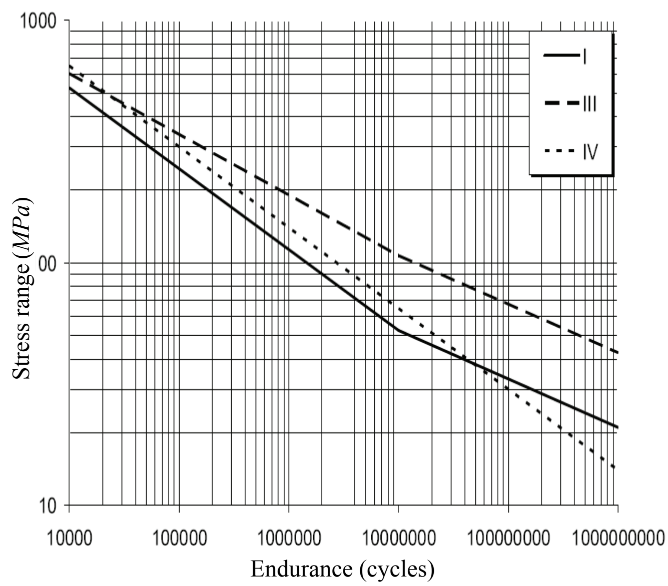

Fig. 3 DNV S-N Curve.

In this paper, we used the S-N curves which are DNV US-I, DNV US-III, ABS C and ABS E for parametric study. In general, these S-N curves are often used for fatigue analysis of hull structure.

Wave scatter data

The wave scatter data are composed with revelation probabilities according to significant wave height and zero-crossing period. The wave scatter data are generally suggested by classification societies and international research institutes. The representative wave scatter data are IACS North Atlantic wave scatter data (IACS NA), ABS unrestricted wave scatter data (ABS unres.), DNV worldwide wave scatter data (DNV WW), WALDEN wave scatter data (WALDEN) and etc. These wave scatter data are generated by measurements of global oceans like the North Atlantic. Another representative wave scatter data are generated by measurements of local oceans like Gulfs, Haltenbanken and etc. The BMT wave scatter data are representative.

Tz(s)	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	Sum
Hs (m)																	
0.5	1.3	133.7	865.6	1 186.0	634.2	186.3	36.9	5.6	0.7	0.1	0	0	0	0	0	0	3 050
1.5	0	29.3	986.0	4 976.0	7 738.0	5 569.7	2 375.7	703.5	160.7	30.5	5.1	0.8	0.1	0	0	0	22 575
2.5	0	2.2	197.5	2 158.8	6 230.0	7 449.5	4 860.4	2 066.0	644.5	160.2	33.7	6.3	1.1	0.2	0	0	23 810
3.5	0	0.2	34.9	695.5	3 226.5	5 675.0	5 099.1	2 838.0	1 114.4	337.7	84.3	18.2	3.5	0.6	0.1	0	19 128
4.5	0	0	6.0	196.1	1 354.3	3 288.5	3 857.5	2 685.5	1 275.2	455.1	130.9	31.9	6.9	1.3	0.2	0	13 289
5.5	0	0	1.0	51.0	498.4	1 602.9	2 372.7	2 008.3	1 126.0	463.6	150.9	41.0	9.7	2.1	0.4	0.1	8 328
6.5	0	0	0.2	12.6	167.0	690.3	1 257.9	1 268.6	825.9	386.8	140.8	42.2	10.9	2.5	0.5	0.1	4 806
7.5	0	0	0	3.0	52.1	270.1	594.4	703.2	524.9	276.7	111.7	36.7	10.2	2.5	0.6	0.1	2 586
8.5	0	0	0	0.7	15.4	97.9	255.9	350.6	296.9	174.6	77.6	27.7	8.4	2.2	0.5	0.1	1 309
9.5	0	0	0	0.2	4.3	33.2	101.9	159.9	152.2	99.2	48.3	18.7	6.1	1.7	0.4	0.1	626
10.5	0	0	0	0	1.2	10.7	37.9	67.5	71.7	51.5	27.3	11.4	4.0	1.2	0.3	0.1	285
11.5	0	0	0	0	0.3	3.3	13.3	26.6	31.4	24.7	14.2	6.4	2.4	0.7	0.2	0.1	124
12.5	0	0	0	0	0.1	1.0	4.4	9.9	12.8	11.0	6.8	3.3	1.3	0.4	0.1	0	51
13.5	0	0	0	0	0	0.3	1.4	3.5	5.0	4.6	3.1	1.6	0.7	0.2	0.1	0	21
14.5	0	0	0	0	0	0.1	0.4	1.2	1.8	1.8	1.3	0.7	0.3	0.1	0	0	8
15.5	0	0	0	0	0	0	0.1	0.4	0.6	0.7	0.5	0.3	0.1	0.1	0	0	3
16.5	0	0	0	0	0	0	0	0.1	0.2	0.2	0.2	0.1	0.1	0	0	0	1
Sum	1	165	2 091	9 280	19 922	24 879	20 870	12 898	6 245	2 479	837	247	66	16	3	1	100 000

Fig. 4 IACS North Atlantic Wave Scatter Data.

Tz(s)	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	Sum
Hs (m)																
1.0	311	2 734	6 402	7 132	5 071	2 711	1 202	470	169	57	19	6	2	1	0	26 287
2.0	20	764	4 453	8 841	9 045	6 020	3 000	1 225	435	140	42	12	3	1	0	34 001
3.0	0	57	902	3 474	5 549	4 973	3 004	1 377	518	169	50	14	4	1	0	20 092
4.0	0	4	150	1 007	2 401	2 881	2 156	1 154	485	171	53	15	4	1	0	10 482
5.0	0	0	25	258	859	1 338	1 230	776	372	146	49	15	4	1	0	5 073
6.0	0	0	4	63	277	540	597	440	240	105	39	13	4	1	0	2 323
7.0	0	0	1	15	84	198	258	219	136	66	27	10	3	1	0	1 018
8.0	0	0	0	4	25	69	103	99	69	37	17	6	2	1	0	432
9.0	0	0	0	1	7	23	39	42	32	19	9	4	1	1	0	178
10.0	0	0	0	0	2	7	14	16	14	9	5	2	1	0	0	70
11.0	0	0	0	0	1	2	5	6	6	4	2	1	1	0	0	28
12.0	0	0	0	0	0	1	2	2	2	2	1	1	0	0	0	11
13.0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	4
14.0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
Sum	331	3 559	11 937	20 795	23 321	18 763	11 611	5 827	2 480	926	313	99	29	9	0	100 000

Fig. 5 DNV Worldwide Wave Scatter Data.

In the spectral fatigue analysis, the wave scatter data are extremely dominant design variable. Therefore, in this paper, we used the wave scatter data which are IACS NA, ABS unres., DNV WW and WALDEN for parametric study.

Wave spectrum

The representative wave energy spectrums are Pierson-Moskowitz wave spectrum and JONSWAP wave spectrum. (Almar, 1985). The spectrums are as follows.

Pierson – Moskowitz wave spectrum :

$$S_\eta(\omega|H_s,T_z) = \frac{H_s^{\,2}}{4\pi}\left(\frac{2\pi}{T_z}\right)^4 \omega^{-5} \exp\left[-\frac{1}{\pi}\left(\frac{2\pi}{T_z}\right)^4 \omega^{-4}\right] \qquad (2)$$

ONSWAP wave spectrum :

$$S_\eta(\omega|H_s,T_z) = ag^2\omega^{-5}\exp\left[-\frac{5}{4}\left(\frac{\omega}{\omega_p}\right)^{-4}\right]\gamma^{\exp\left(-\frac{(\frac{\omega}{\omega_p}-1)^2}{2\omega^2}\right)} \qquad (3)$$

The Pierson-Moskowitz wave spectrum is generally used for spectral fatigue analysis of usual vessels because the Pierson-Moskowitz wave spectrum is used for fully developed sea. On the other hands, the JONSWAP wave spectrum is used for non-fully developed sea. In this paper, we used these two wave spectrums for the parametric study.

Bandwidth effect

In the spectral fatigue analysis, the short-term distribution of stress ranges is generally assumed to be the Rayleigh distribution, because the Rayleigh distribution is able to be easily calculated with Gamma function.

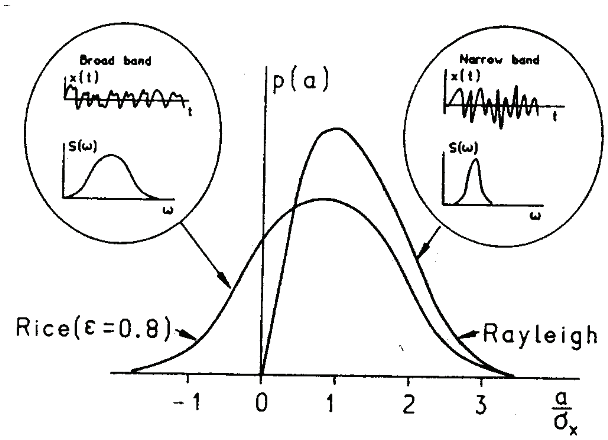

Fig. 6 Rice distribution and Rayleigh distribution.

The Rayleigh distribution is suitable for the narrow-banded data which has zero bandwidth parameter ($\varepsilon = 0$).

$$\varepsilon = \left(1 - \frac{m_2^{\,2}}{m_0 \cdot m_4}\right)^{\frac{1}{2}} \qquad (4)$$

But the short-term distribution of stress ranges has not zero bandwidth parameter practically. Therefore, some errors are occurred in the calculation when this assumption used. In order to correct these errors, the rainflow bandwidth correction factor is used.

$$\lambda_{ij} = a + (1-a)(1-\varepsilon_{ij})^b \qquad (5)$$

$$a = 0.926 - 0.033m\,,\ \ b = 1.587m - 2.323$$

In this paper, we analyzed the results of difference whether applying this correction factor or not in the parametric study.

SPECTRAL FATIGUE ANALYSIS FOR 170K LNGC

In this paper, the spectral fatigue analysis was performed for 170*k* LNGC. The Fig.7 is panel elements for calculation of hydrodynamic response. The hydrodynamic analysis was performed by WASIM in the DNV SESAM Program. The range of wave frequency is from 0.2 *rad/s* to 1.8 *rad/s*, and the range of heading angle is from 0° to 330° and the increment is 30°.

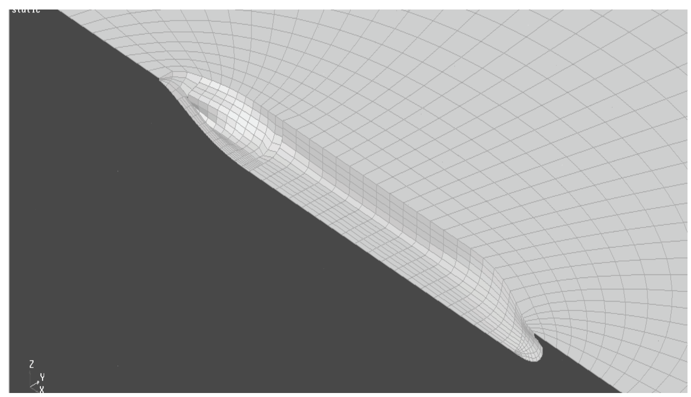

Fig. 7 Panel Elements for Calculation of Hydrodynamic Response.

The Fig. 8 is global FE model for global structural analysis. The global structural analysis was performed by SESTRA in the DNV SESAM Program.

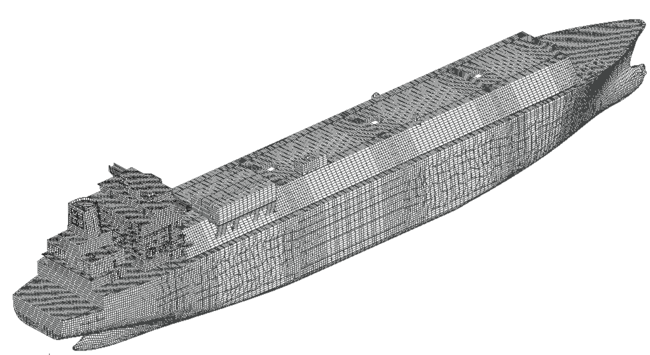

Fig. 8 170k LNGC Global FE Model.

The Fig. 9 is local fine FE model for local structural analysis. The assessment sites are upper hopper knuckle and lower hopper knuckle.

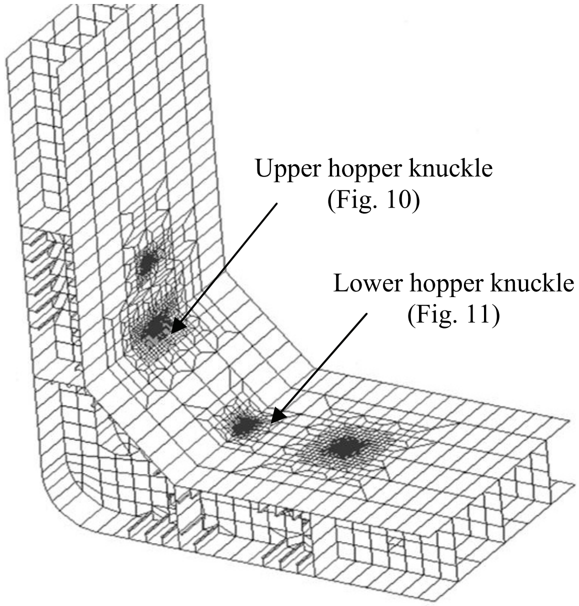

Fig. 9 Local FE Model of Lower Hopper Knuckle.

The fatigue damages were calculated for 4 elements in the each hotspot. These elements are as follows.

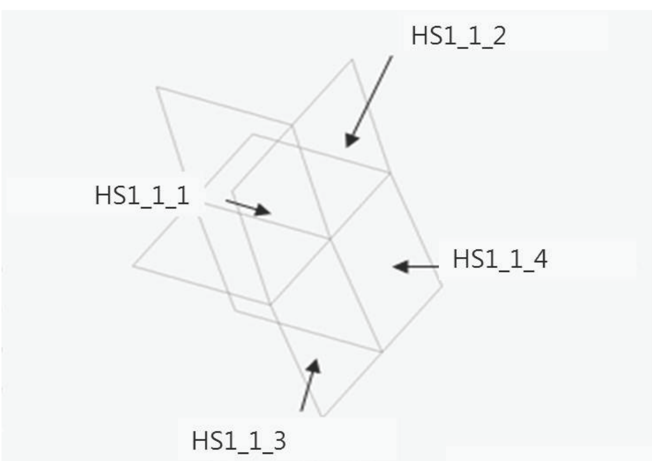

Fig. 10 Hotspot of Upper Hopper Knuckle.

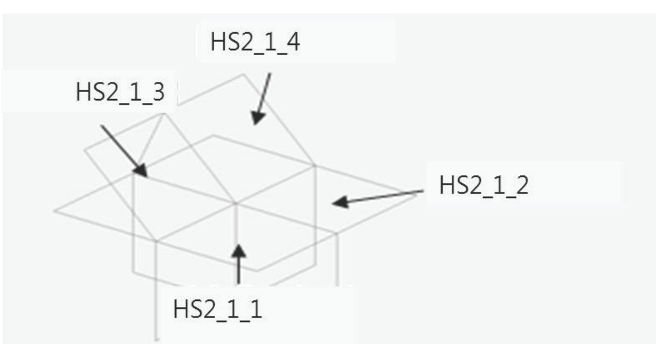

Fig. 11 Hotspot of Lower Hopper Knuckle.

The calculation of fatigue damage was performed by STOFAT in the DNV SESAM Program.

RESULTS OF PARAMETRIC STUDY

S-N curve

Table 3 Fatigue Damage due to S-N Curve (1).

	HS 1_1_1	HS 1_1_2	HS 1_1_3	HS 1_1_4
DNV US-I	0.4021	0.3648	0.2817	0.2474
DNV US-III	0.0184	0.0163	0.0118	0.0101
ABS C	0.0698	0.0618	0.0451	0.0383
ABS E	0.6221	0.5669	0.4420	0.3902

Table 4 Fatigue Damage due to S-N Curve (2).

S-N Curve	HS 2_1_1	HS 2_1_2	HS 2_1_3	HS 2_1_4
DNV US-I	0.0962	0.0873	0.1937	0.1674
DNV US-III	0.0033	0.0030	0.0075	0.0063
ABS C	0.0122	0.0109	0.0285	0.0239
ABS E	0.1574	0.1433	0.3082	0.2679

Wave scatter data

Table 5 Fatigue Damage due to Wave Scatter Data (1).

Wave Scatter Data	HS 1_1_1	HS 1_1_2	HS 1_1_3	HS 1_1_4
IACS NA	0.4021	0.3648	0.2817	0.2474
ABS unres.	0.4186	0.3832	0.2949	0.2617
DNV WW	0.1548	0.1413	0.1057	0.0934
WALDEN	0.2341	0.2148	0.1634	0.1454

Table 6 Fatigue Damage due to Wave Scatter Data (2).

Wave Scatter Data	HS 2_1_1	HS 2_1_2	HS 2_1_3	HS 2_1_4
IACS NA	0.0962	0.0873	0.1937	0.1674
ABS unres.	0.1189	0.1102	0.2138	0.1887
DNV WW	0.0471	0.0443	0.0794	0.0706
WALDEN	0.0876	0.0835	0.1306	0.1182

Wave spectrum

Table 7 Fatigue Damage due to Wave Spectrum (1).

Wave Spectrum	HS 1_1_1	HS 1_1_2	HS 1_1_3	HS 1_1_4
P-M	0.4021	0.3648	0.2817	0.2474
JONSWAP	0.4714	0.4228	0.3327	0.2882

Table 8 Fatigue Damage due to Wave Spectrum (2).

Wave Spectrum	HS 2_1_1	HS 2_1_2	HS 2_1_3	HS 2_1_4
P-M	0.0962	0.0873	0.1937	0.1674
JONSWAP	0.0913	0.0817	0.2110	0.1802

Rainflow bandwidth effect

Table 9 Fatigue Damage due to application of bandwidth effect (1).

Bandwidth Effect	HS 1_1_1	HS 1_1_2	HS 1_1_3	HS 1_1_4
Applied	0.4021	0.3648	0.2817	0.2474
Non-applied	0.4705	0.4268	0.3324	0.2919

Table 10 Fatigue Damage due to application of bandwidth effect (2).

Bandwidth Effect	HS 2_1_1	HS 2_1_2	HS 2_1_3	HS 2_1_4
Applied	0.0962	0.0873	0.1937	0.1674
Non-applied	0.1203	0.1091	0.2402	0.2076

CONCLUSIONS

In this paper, the parametric study was performed considering effects of the variables which are S-N curve data, wave scatter data, wave spectrum and bandwidth correction factor. The results are summarized as follows.(Table 11)

The parametric study based on the spectral fatigue analysis is hard to perform, because the spectral fatigue analysis has complex and difficult processes. The results of this paper contribute to resolve this problem.

The basic research for understanding effects of these variables to the fatigue damage was established in this paper. We are able to use these results to determine the design variables in the spectral fatigue analysis for the reference. And the results enhance the understanding about the procedure of the spectral fatigue analysis where these variables were used in.

Table 11 Results of Parametric Study.

S-N Curve	Wave Scatter Data	Wave Spectrum	Rainflow Bandwidth Effect	D [%]
DNV US-I	IACS NA	P-M	Applied	100
DNV US-III	IACS NA	P-M	Applied	4.1
ABS C	IACS NA	P-M	Applied	15.3
ABS E	IACS NA	P-M	Applied	158.5
DNV US-I	ABS unres.	P-M	Applied	110.4
DNV US-I	DNV WW	P-M	Applied	41.3
DNV US-I	WALDEN	P-M	Applied	78.8
DNV US-I	IACS NA	JS	Applied	110.3
DNV US-I	IACS NA	P-M	Non-Applied	120.9

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