Analysis of Crack Retardation Effects and Crack Path in Ship Structure Members on Different Routes

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Abstract The ship size has been rapidly increased in recent years. Consequently, many aspects of ship structural safety have been concerned, i.e. fatigue strength. Since fatigue cracks are found in the early stage of a ship's service life, it might be that the classical cumulative fatigue rule is insufficient to consider the effects of many uncertain factors, such as variable wave environment loads. The wave load history hinges on the short-sea history. It means that the accuracy of fatigue assessment is affected by the used wave model. There are several established wave models, which could be used to simulate wave load history as in the real ocean conditions. In this paper, wave load histories of a 2800TEU container ship are generated by two different wave models. It is used for crack propagation analysis in the changing routes and trades. The result in the simulated crack propagation lives is examined and discussed.

Keywords fatigue crack propagation, fatigue damage sensor, hindcast data, ship structures

1. Introduction

Fatigue is an important issue for maritime industry. Large ship designers must consider the fatigue strength of ship structures. The traditional ship fatigue assessment is conducted by using a simplified method, in which Palmgren-Miner linear cumulative law and S-N curves are used. In this method, all parameters are provided by classification societies' rules. A comparative study shows that this method gives wide scatter of fatigue life predictions [1]. Thus, fatigue cracks are observed much earlier than expected, challenge the safety of structural integrity and final failure in shipping. This is caused by many uncertain factors, e.g. chosen S-N parameters, load spectrum range, fatigue assessment method, etc.

The solving alternately starts from how to get the structural stress history for various sea-states. A sea-state is characterized by its energy spectra, which is a function of significant wave height (*Hw*) and mean wave period (*Tw*). The transfer function of structural stress response, also known as RAOs, is obtained from a direct calculation by considering wave loads for all loading conditions, ship speeds, and heading angles. It can be combined with the wave energy spectrum of a sea state to compute the stress spectrum. The fatigue crack propagation theory is capable to predict fatigue crack propagation length in a real service voyage [1][2].

The accuracy of fatigue propagation analysis hinges on the load sequence's reproducibility of the actual sea-state history. Ship owners' concern about fatigue damage is growing, and the ship operation / route is changed constantly according to the weather condition. The load sequence obtained from the wave scatter diagram in classification society rules may be different from that of the actual load [3]. This may affect the accuracy of the crack propagation analysis.

Recently, many sources of wave data, i.e. hindcast, satellite measurement, and onboard measurement can be utilized for load history simulation. In this study, the effect of the wave environments encountered by a 2800TEU container ship in North Atlantic Ocean on the fatigue crack propagation life is discussed. The crack propagation analyses are conducted by using stress histories simulated from the ship's encountered sea-state history. In these simulations, two stochastic wave models are utilized, and the difference in the simulated crack propagation lives is examined.

2. The two established wave models

This section explains the capability and reliability of two wave models in load sequence and fatigue damage estimation. These wave models are developed based on statistical analysis of ocean wave measurements. The first model is the 'Spatio-temporal wave model' developed by using satellite wave data [5]. The other model is the '3G-storm model' developed by using the hindcast data [7]. The target ship is a 2800TEU container ship. The sea-states were measured onboard on this ship, and the onboard data are used as a reference. The ship sailed on the North Atlantics routes in the first half-year of 2008 as shown in Fig. 1. Details of this target ship are described in [4].

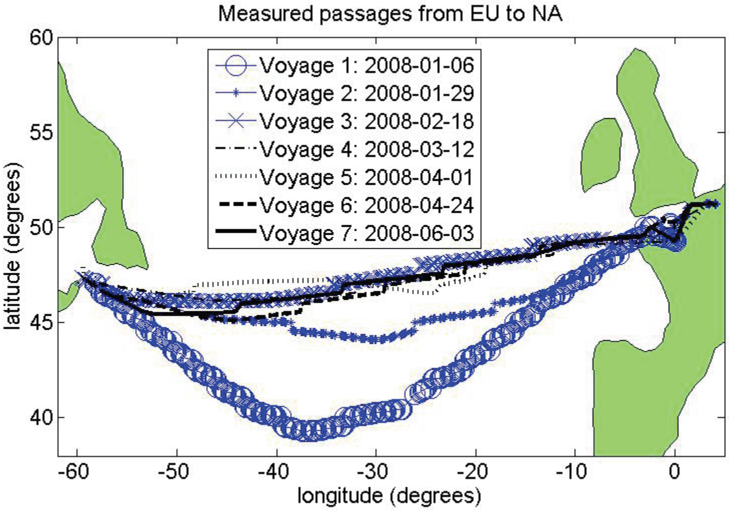


Figure 1. Voyage from EU to USA of 2800TEU container ship along first semester of 2008
(the arrival date of each voyage is indicated in the legend) [3].

2.1 The spatio temporal wave model

The significant wave height *Hw* at position ***p*** and time *t* is accurately modeled by means of lognormal cumulative distribution function (cdf). Let *X(**p**,t)* = *ln(Hw(**p**,t))* denote a field of logarithms of significant wave height that evolves in time. For a fixed *t*, the local field *X(**p**,t)* is assumed to be homogeneous Gaussian with covariance changes for the location ***p***. The Gaussian field *X(**p**,t)* is assumed to have a mean that varies annually due to the periodicity of the climate. In the model, the mean value of the Gaussian field is assumed as:

$$\mu(t) = E\left[\mathrm{X}(p,t)\right] = \beta_0 + \beta_1 \cos(\phi t) + \beta_2 \cos(\phi t) + \alpha t \tag{1}$$

where $\phi = {}^{2\pi}\!/_{365.2}$ is chosen to give an annual cycle for time in days. The parameters in Eq. (1)

can be computed from the satellite measurements.

Suppose t_0 be the starting date of a voyage, and the position on the planned route is given as $\boldsymbol{p}(t) = (x(t), y(t))$, for the time period $[t_0, t_1]$, and the ship's velocity as $v(t) = (v_x(t), v_y(t))$. For a given route let $z(t) = X(\boldsymbol{p}(t),t)$ be the encountered logarithms of *Hw*. (The encountered significant wave height is $Hw(t) = exp(z(t))$.) Obviously it will be different for $\boldsymbol{p}$ close to the coast and for $\boldsymbol{p}$ in the middle of the ocean. Hence, the encountered process $z(t)$ will be Gaussian but non-stationary.

In principle, the mean value and variance of the Gaussian field are needed in order to compute the distribution of *Hw* along the route. The covariance structure should also be provided if the variance of fatigue damages is required. In general, the data from both satellites and buoys are necessary to get the parameters of the covariance structure in the model. The median value of *Hw* in February and August in the spatio-temporal model is shown in Fig. 2. Further description of the model can be referred to [5].

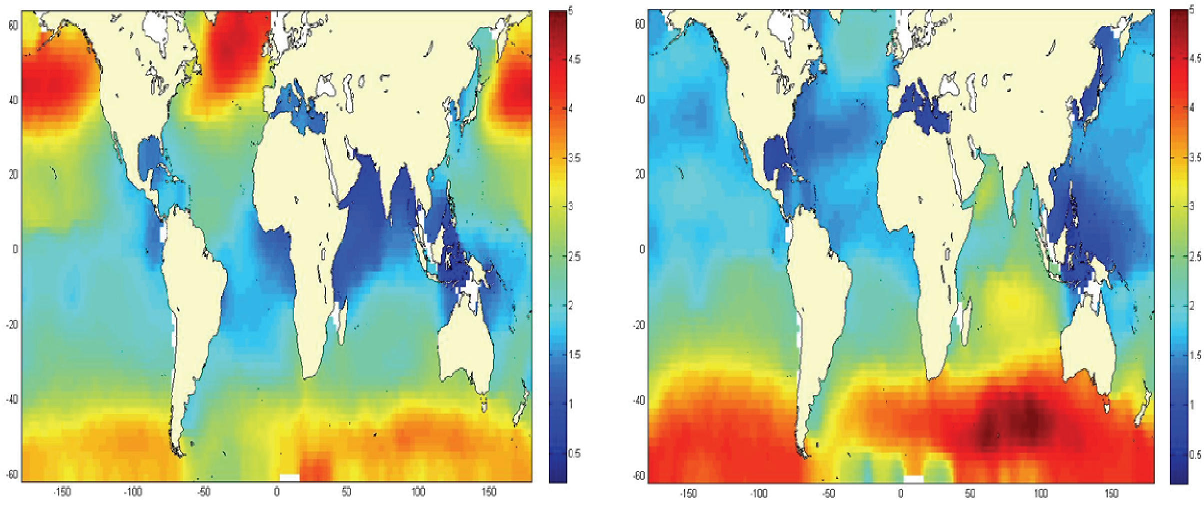


Figure 2. The median value of *Hw* (meters) in February (left) and in August (right).

2.2 The 3G-storm model

In order to simulate load sequences in the real oceans, Tomita [6] proposed the storm model. It was assumed that ocean conditions could be classified into either calm-sea or storm. Calm-seas are modeled as time-independent random waveforms, while storms are modeled as individual wave sequences with crescendo de-crescendo amplitude waveforms. Tomita's storm model was modified by Prasetyo and Osawa [7] so that the correlation between *Hw* and *Tw* and the variance of storm duration can be taken into account. This modified model is called '3G-storm model'. Storm profiles are determined by assuming that the long-term probability distribution of *Hw* obeys Weibull distribution [6]. The detail and procedure to determine storm profile parameters is described in [7]. Once *Hw* is determined, *Tw* is determined by using a wave scatter diagram (a joint probability distribution of *Hw* and *Tw*, $P(Hw,Tw)$).

2.3 Comparison of the two wave models

Figure 3 shows the comparison of probability density function (pdf) of *Hw* simulated by using the spatio-temporal wave model and the 3G-storm model along the North Atlantic voyages of Fig. 1. In this figure the pdf of H_w from the onboard measurement and that provided in DNV recommendation [8] are also presented. This figure shows that both wave models give more frequent mid-range waves (2m < *Hw* < 4m) than the onboard measurement and the DNV recommendation. The fatigue damage accumulated during 7 voyages of Fig. 1 is compared and presented in Table 1. Two wave models give about 25% overestimation comparing with the total rainflow damages which is computed using the recorded stress signals. Generally speaking, for each voyage, the difference of fatigue damage is negligible except the voyage 2008-06-03. It means that the two wave models could be used for the design purpose to generate *Hw* history and fatigue damage estimation.

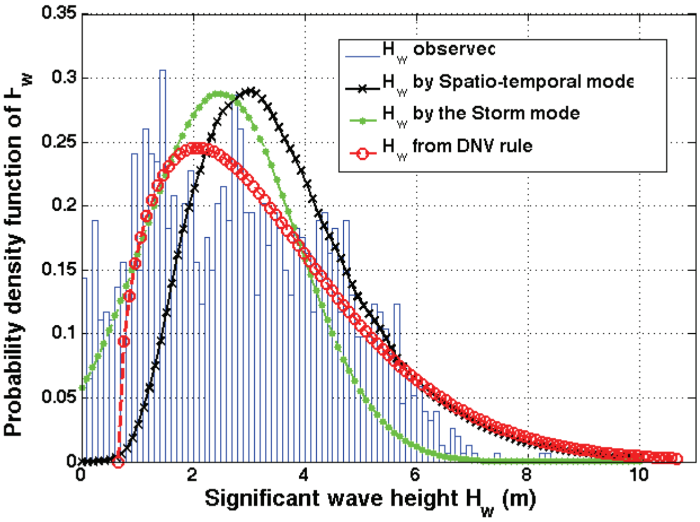


Figure 3. Probability density function (PDF) of *Hw*.

Table 1. Calculated Fatigue damage by using *Hw*, that generate from both wave models and rain-flow damage of observed voyage.

Voyage	Observed voyage	Spatio-temporal model	3G-storm model
Voy. 2008-01-06	0.0080	0.0077	0.0078
Voy. 2008-01-29	0.0057	0.0075	0.0073
Voy. 2008-02-18	0.0045	0.0067	0.0063
Voy. 2008-03-12	0.0014	0.0032	0.0028
Voy. 2008-04-01	0.0032	0.0041	0.0030
Voy. 2008-04-24	0.0027	0.0019	0.0029
Voy. 2008-06-03	0.0007	0.0010	0.0026
Sum:	0.0262	0.0321	0.0325

3. Fatigue crack propagation analysis

3.1 Comparison of stress history

Sea-state histories (*Hw*, *Tw*) can be simulated by the 3G-storm model. Once a sea-state is simulated, the stress history can be generated by using the wave spectrums and the transfer function of ship structural stress, known as RAO. Once (*Hw*, *Tw*) are given, the power spectral densities of wave, $S(\omega)$, is determined. Ocean wave spectrums such as JONSWAP spectrum, modified Pierson-Moskowitz (ISSC) spectrum [9] are utilized in this analysis. In the stress calculation, the history of the ship's heading angle to the wave, χ, is needed because the RAO depends on not only *Hw* and *Tw* but also χ. Once *Hw*, *Tw* and χ are given, the power spectral densities of stress is determined as the cross spectrum, then the individual stress waveform is generated by assuming that the stress amplitude follows Rayleigh distribution whose parameter are determined from the cross spectrum.

The cdf of *Hw* is estimated by the spatio-temporal wave model at a given time and point. Once the probability distribution of *Hw* is given, the energy spectrums of wave and stress response can be computed by using ocean wave spectrums and RAOs for stress response. It is known that for fatigue assessment, the ship structural stresses can be assumed to Gaussian distributed. For one stationary sea-state, the Gaussian stresses are fully defined by its spectral density and the mean value. Hence, one could also simulate the stress signal from the obtained stress spectral density for each sea-state; see Fig. 4 for an example.

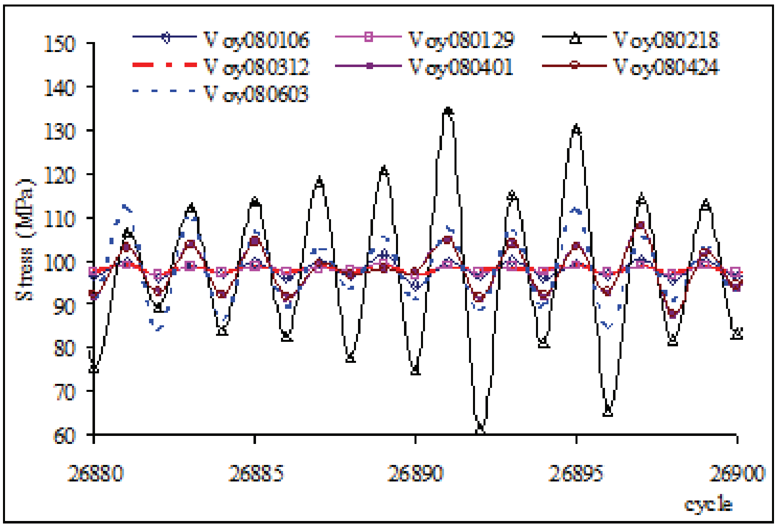


Figure 4. Examples of simulated stress histories of the 2800TEU container ship for different voyages from EU to USA using the 3G-storm model' in a certain cycle.

In the following discussion, the stress history generated by 3G-storm model is called 'model 1', and that generated by the spatio-temporal wave model is called 'model 2'. In order to make the maximum stress amplitude of two histories to be of almost equal level, the simulated stresses are normalized by a correction factor. Figure 5 shows the relation between the stress amplitude S_a and the occurrence frequency. The S_a threshold of crack propagation for the given initial crack size, $S_{a,th}$=49.5MPa, is presented in this figure. It is shown that the occurrence frequency of S_a derived from Spatio temporal model is larger than that of 3G-stom model for cases where $S_a > S_{a,th}$.

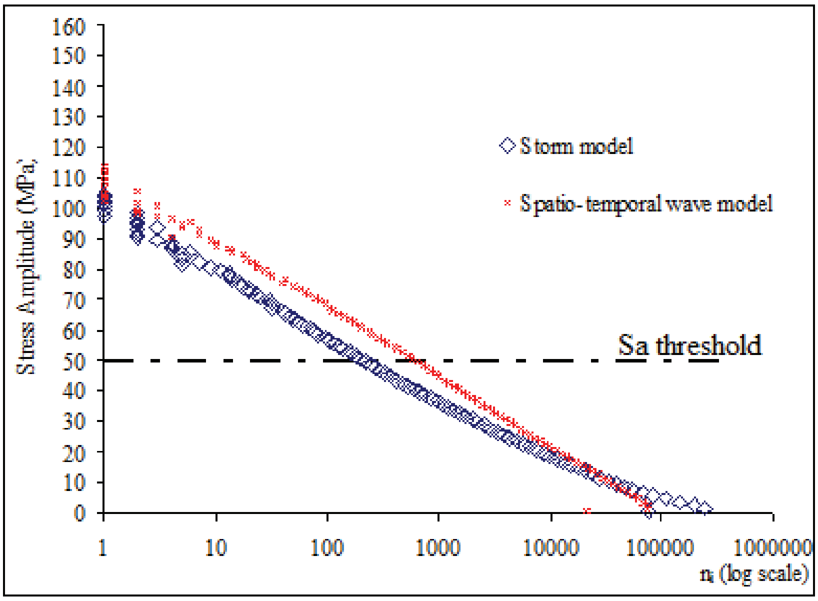


Figure 5. The relation between the stress amplitude S_a and the occurrence frequency of stress histories generated by the 3G-storm and spatio-temporal wave models.

3.2 Fatigue crack propagation model and analyses

Fatigue crack propagation analysis might concern some uncertainty factors on its computation [1]. Analyses results depend on crack growth formula and the accuracy of stress intensity factor (SIF) calculation. In this study, crack propagation is computed by FASTRAN II [12], which is based on cohesive yield model and crack closure concept. The software was developed using crack closure concept [11][12]. Details of the background theory of this code are described by Newman [11][12]. In this study, the crack propagation of a surface crack in a weld of ship structural member is analyzed. SIF range ΔK is calculated by using the modified Newman-Raju formula [10], given as:

$$\Delta K = K_s.M_k.\left(\Delta\sigma_m.F_m\left(c,a,t\right)+\Delta\sigma_b.F_b\left(c,a,t\right)\right)\sqrt{\pi a} \tag{2}$$

where, K_s is the stress concentration factor of structural detail, and it can be calculated by FE direct calculation or by using the engineering formula provided by classification society rules. M_k F_b and F_m are correction factor for weld bead and finite plate size, and they are presented in [10]. The parameters a and c are the depth and surface length of a semi elliptical surface crack defined in Fig. 6 and t is the thickness of the main plate.

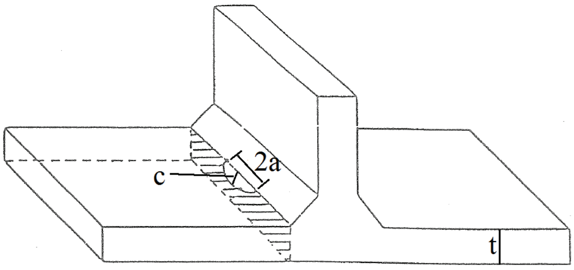


Figure 6. Typical semi-elliptical surface crack on weld toe of fillet weld joint.

The crack growth rate is calculated by modified Paris-Elber law (Eq.3):

$$\frac{da}{dN} = C\left\{\left(\Delta K_{eff}\right)^m - \left(\left(\Delta K_{eff}\right)_{th}\right)^m\right\} \tag{3}$$

where C and m are the material parameters. ΔK_{eff} and $\left(\Delta K_{eff}\right)_{th}$ are the effective SIF range and its threshold.

3.3 Results: fatigue propagation analyses

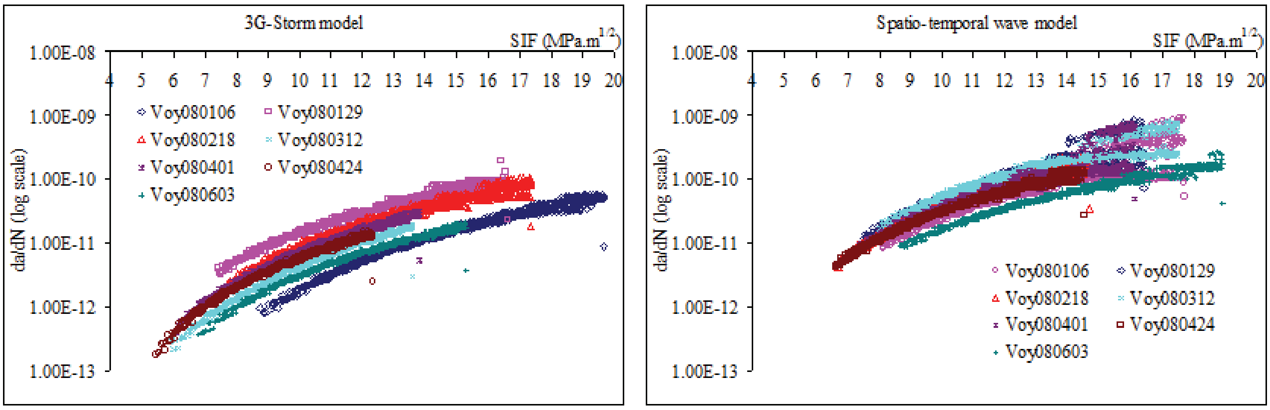
The crack propagation analysis of two stress histories (model 1 and model 2) is conducted. The initial surface crack length is 0.2 mm, and the initial aspect ratio is 1/2. The propagation analyses are continued until the crack depth exceeds 8 mm or the surface length exceeds 10 mm. Crack growth is computed by using Eq. (3). The material parameters, C and m are 1.45e-11m/cycle and 2.75, respectively. Let Sa_{th} be the threshold of stress range so that the initial crack can growth. The threshold of the stress intensity $\left(\Delta K_{eff}\right)_{th}$ is equal to 2.45MPa.m$^{1/2}$ and Sa_{th} is about 49.5MPa. The stress history is simulated 15 trials in order to provide statistical data of crack propagation analysis and the mean stress is chosen to be 98.0MPa.

The statistics of propagation lives analyzed is presented in Table 2. Figure 7 shows the comparison of the relationship between the growth rate and SIF range for the cases with the shortest propagation life as listed in Table 2. In this table, it is shown that the model 1 leads to longer lives than those of model 2 in most voyages while fatigue damages derived from these two models are almost equal (see Table 1). The model 2 leads to rapid crack growth rate for the cases with same SIF range (i.e. 14MPa.m$^{1/2}$ $\leq$ SIF $\leq$ 17MPa.m$^{1/2}$) than the model 1 as seen in Fig. 7.

It is supposed that the retardation of crack growth rate for the cases of model 1 is caused by the excessive load of the generated storm state in Hw history. This shows that the loading sequence of the excessive load affects to crack propagation behavior.

Table 2. Calculated crack propagation life of stress history that it is computed using the 3G-storm model and the spatio-temporal model.

Voyage		Model 1 Crack propagation life (1e6 cycles)				Model 2 Crack propagation life (1e6 cycles)			
No	Arrival Date	Mean	Max.	Min.	Std.Dev	Mean	Max.	Min.	Std.Dev
1	20080106	2590	8034	782	1694	568	1768	137	498
2	20080129	1019	2244	305	506	1805	18807	99	4794
3	20080218	1181	3030	386	675	679	1856	209	542
4	20080312	11658	37885	2269	8431	2033	13120	71	4429
5	20080401	8320	17411	1285	4776	438	1494	146	385
6	20080424	11537	30086	2769	9188	8218	56415	264	14740
7	20080603	7901	30192	1848	7447	18215	54144	170	19633



a) 3G-storm model b) Spatio-temporal wave model

Figure 7. Computed crack growth related with stress intensity factor by using the 3G-storm model and the Spatio-temporal wave model for the cases with the shortest propagation life as listed in Table 2.

4. Conclusions

Wave environment loads could be simulated based on different wave models for the fatigue strength assessment. In this study, two different wave models (the spatio-temporal wave model and the 3G-storm model) are compared with the onboard measurement of a 2800TEU containership. The comparison shows that the two wave models give the same probability density function of *Hw* along these measured routes. Subsequently, the generated stress history could be obtained for different routes, but there is some difference in occurrence frequency of stress amplitude computing from stress spectra.

Retardation and acceleration of crack growth is shown by optimizing different routes with simulated load sequence of two wave models. The crack propagation analysis can be utilized in ship design to be more realistic.

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