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A Comparative Study on Fatigue Damage using a Wave Load Sequence Model

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Abstract

Despite that ships get the approval of classification societies and structural members are designed to survive random environmental conditions for twenty or twenty-five years, fatigue crack damage still occurs. Nowadays, the operation based on weather routing programs has become important, not only to avoid adverse sea conditions that can cause damage, time loss or significant speed reduction but also to improve the crew safety. In this paper, S-N based fatigue assessment of a welded joint in an ocean going is performed. It is assumed that the ship sails following a planned route and a route based on weather conditions. Short sea sequences are generated by a storm model called "4G Storm Model", proposed by one of the co-authors (De Gracia et al., 2017). Stress histories are generated considering the stochastical nature of the wave direction variation. Cumulative fatigue damage is performed following a classification society rule. Based on these results, the effect of ship routing and headings model on the S-N fatigue assessment is discussed.

Keywords: Weather routing, fatigue, cumulative damage, storm model, wave sequence model.

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1. Introduction

A fatigue assessment is one of the necessary assessments for the present rules of major Classification Societies (CS). These rules are based on the linear cumulative damage law (e.g., Miner's law), and fatigue damage still occurs at the welded joints (Wang et al., 2002). There are reports that state that not a few premature fatigue failures are found in ship structures (Storhaug et al., 2007). Fatigue damage in ships is mainly caused by the variation of wave loads acting on ship structures. A reliable description of fatigue loads is important in order to improve the accuracy of the fatigue assessment of ship structures (Mao et al., 2013). A wave load sequence model, called 'storm model', that can simulate wave load sequence experienced by ocean-going ships was proposed by Tomita (1992). Kawabe et al. (2003) and Prasetyo et al. (2012) modified Tomita's model to improve the emulation capability of real sea state sequence. In these earlier studies, it was assumed that ships sail along great circle routes, and the stress response was evaluated by adopting the "all headings" model. Recently, ship operation based on weather routing has become pervasive these days in order to avoid severe weather conditions. Therefore, it is important to understand the long-term wave loads acting in the ship hull of those ships compared to those who follow a planned route (great circle route). To understand the effect of the headings model and weather routing on the ship structural members, De Gracia et al. (2017) proposed a storm model that consider the stochastic nature of the wave direction for the evaluation of stresses of the ocean-going ship due to wave loads, based on Prasetyo's model. He reported that the storm model results tends to overestimate the stress sequence estimation. This study covers the improvement of the stress sequence history generation from the storm model applied to weather routing. A practical case of a container ship that sails in a Pacific Ocean route is presented. Fatigue damage of a welded joint is performed. The ship is assumed to follow a Great Circle Route (GCR) and a Minimum Time Route (MTR). Short sea state sequences are generated by using Japan Weather Association (JWA) hindcast data, and those for MTR are simulated by adopting a weather routing algorithm (Tamaru, 2016). An SN-based fatigue assessment is performed for both wave load sequences, and the effect of the ship routing on fatigue damage is evaluated.

2. Oceanographic Data

2.1. Weather Routing Algorithm

The objective of the ship weather routing is maximizing safety and crew comfort, minimum fuel consumption, minimum time underway. The optimum sail will depend on the sea conditions, the forecast of weather, and a ship's individual characteristics for a particular transit. Tamaru (2016) proposed a weather routing algorithm which can decide the minimum time route (MTR) from a spatiotemporal distribution of sea states (significant wave height H_S and wave direction θ). The ship route is optimized by analyzing isochrones. The relationship between ship speed loss, significant wave height, and the relative heading angle is taken into account, and the spatiotemporal sea state data was generated from JWA's hindcast data.

2.2. Sea State Data and Shipping Route

A shipping route between San Francisco and Tokyo is considered. GCRs and MTRs are determined by Tamaru, explained in 2.1. The target of this study is a container ship. It is assumed that she sails in the Pacific Ocean for 10 years. The ship experiences the sea state (significant wave height H_S, mean period T_S and wave direction θ) sequence determined by those at the nearest JWA hindcast data grid point. The arrangement of data grid points is shown in Fig. 1.

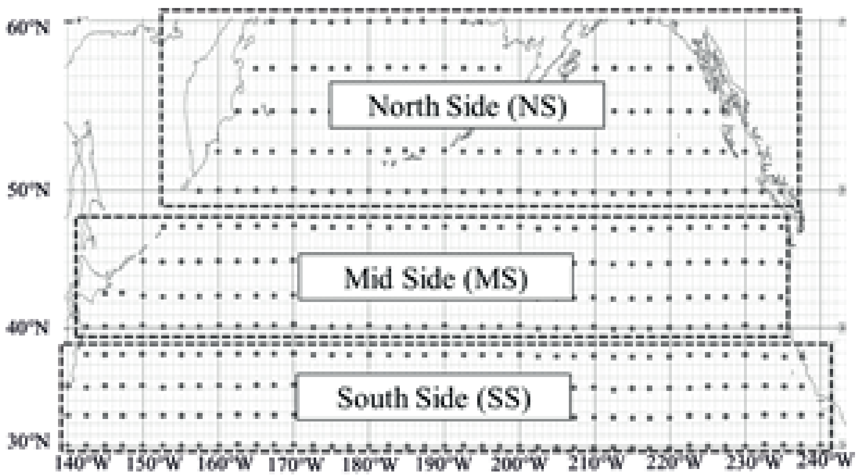

Figure 1: JWA hindcast sea zones in North Pacific Ocean.

2.3. Ship Directional Model

During a ship life, she meets each new wave at a particular relative angle. Let θ, α and χ be the wave direction, ship's heading angle and relative heading angle. The conventional fatigue design procedure, the stress response is calculated by adopting the 'all headings model - AH' in which χ is given by a uniform random number. In this paper, the stress response is calculated by adopting the 4G Storm model (De Gracia et al., 2017), in which the χ's occurrence probability, f_χ, is taken into account, and is called 'real headings model - RH'. f_χ can be determined from θ's occurrence probability, f_θ. Fig. 2 shows a single averaged f_θ zone is determined from JWA hindcast data and the determined f_θ. It is shown that θ is predominant between 210° and 330°. It is also presented the conventional assumed all headings model compared with the average results of the real headings model.

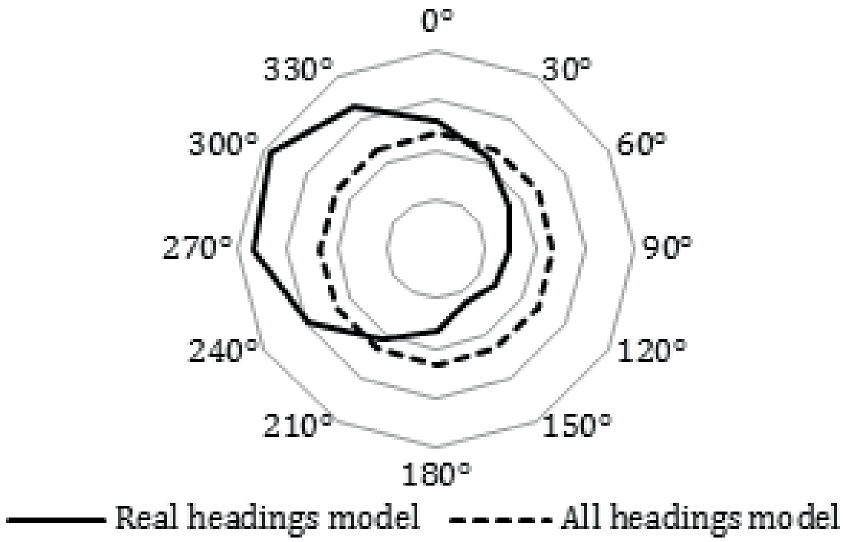

Figure 2: Wave direction's occurrence probability distribution f_θ determined from JWA hindcast data in the North Pacific Ocean.

2.4. Wave Statistics

The 'as-simulated sea sequence' is the sea state sequence directly determined from the GCR or MTR ship position sequence and JWA hindcast data's spatiotemporal wave data, and 'storm sea sequence' be that generated from a storm model simulation. This spatiotemporal wave data is fitted by the log-normal distribution proposed by Wan and Shinkai (1995) due to rounding errors founded in the histograms, which tends to overestimate the long-term distribution of the significant wave height when weather routing is considered. Figure 3 (a), (b) shows the comparison of H_S's exceedance probability $P_{ex,Hs}$ of as-simulated and storm model sea sequence for GCR and MTR routes, respectively. It is shown that the difference in $P_{ex,Hs}$ becomes larger for H_S > 5m, and the difference becomes larger with the increase in H_S in the storm model case, while the difference in the as simulated cases tends to be almost constant with the increase of H_S. It is also noted that the $P_{ex,Hs}$ for GCR in the higher waves range is larger than those from MTR for the case of the as simulated sequence.

3. STRESS RESPONSE

3.1. Stress Statistics

Let $P_{ex,\Delta S}$ be ΔS' exceedance probability. Let $P_{ex,\Delta S|GCR}$ and $P_{ex,\Delta S|MTR}$ be $P_{ex,\Delta S}$ of as-simulated stress sequences for GCR and MTR routes. Figure 4 shows a comparison

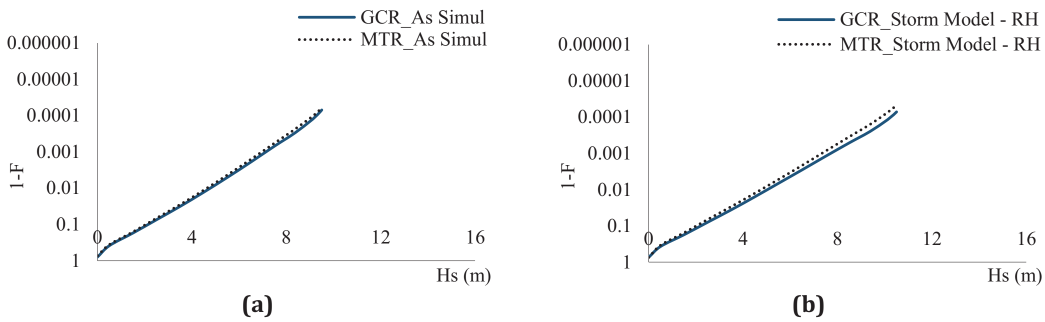

Figure 3: The comparison of significant wave height's exceedance probability $P_{ex,Hs}$ for as-simulated (a) and storm model-real headings (b) sea sequence for MTR and GCR routes.

between $P_{ex,\Delta S|GCR}$ and $P_{ex,\Delta S|MTR}$. It is shown that the difference becomes evident for $\Delta S > 250$MPa, and the difference becomes nearly constant with the increase in ΔS. This difference corresponds the difference in $P_{ex,Hs}$, and the difference in $P_{ex,\Delta S}$ is smaller than that in $P_{ex,Hs}$. This is considered due to the χ's randomness and the variation in RAO associated with χ.

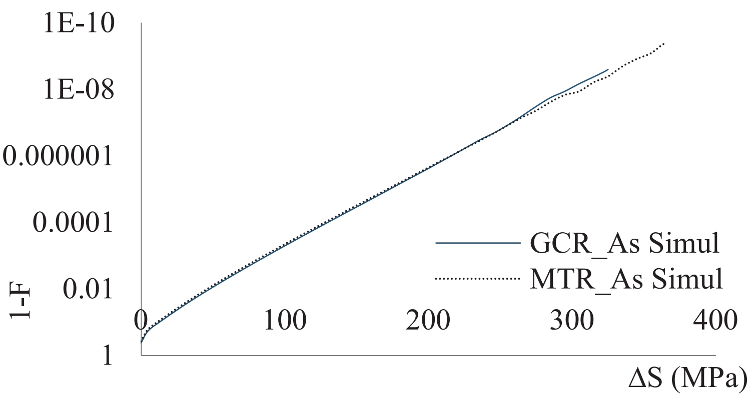

Figure 4: The comparison of stress range's exceedance probability $P_{ex,\Delta S}$ for as-simulated stress sequence for MTR and GCR routes.

4. Wave Load Model for Weather Routing Cases

4.1. Wave Scatter Diagrams

The joint frequency distributions of (H_S, T_S), known as the wave scatter diagrams, are generated by counting sea states recorded in as-simulated sea sequences for GCR and MTR routes. These histograms include rounding errors. These errors are corrected by using the correcting method proposed by Wan and Shinkai (1995). In this method, histograms are fitted with the conditional log-normal distribution $p(T_S|H_S)$, and the

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H_S's marginal probability distribution p(H_S) obtained as in section 2.4. Therefore, the joint probability distribution p(H_S, T_S) is calculated by Eq. (1).

$$p\left(H_S, T_S\right) = p\left(H_S\right) p\left(T_S H_S\right) \tag{1}$$

Figure 5 (a), (b) shows the comparison between $P_{ex,Hs}$ of the as simulated and that of regressed by using Weibull distribution. This figure shows the reasonable agreement of the regressed joint frequency distribution with that of the as simulated.

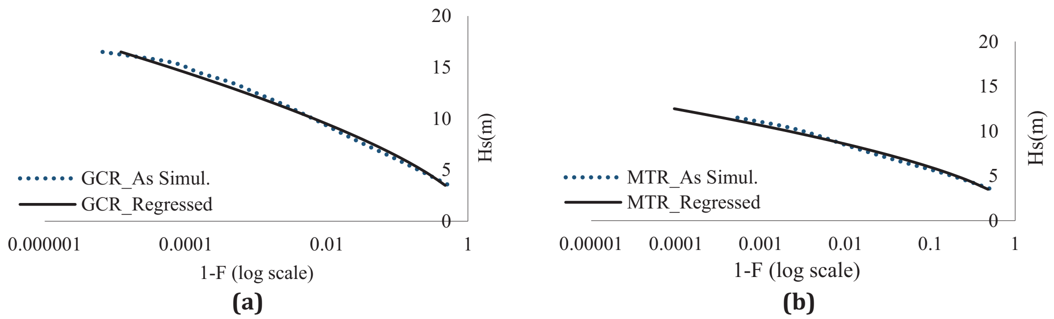

Figure 5: $P_{ex,Hs}$ comparison of the North Pacific Ocean on the GCR and MTR routes. The as simulated data and the regressed based on the Weibull distribution is compared.

4.2. Storm Models

'Storm model' is composed of 'storm profiles' and H_S's probability distribution in calm seas. The 'Storm profiles' are a set of storm waveforms and the occurrence probability of storms. These configurations are determined from the regressed wave scatter diagrams for GCR and MTR routes determined before. In this study, storm profiles are determined by adopting the 4G Storm model. Once a storm model is established, sea sequences (H_S, T_S, χ) are generated from the storm model. From these sea sequences, stress sequences are generated by adopting all headings or real headings models. Let $P_{ex,\Delta S,storm}$ be ΔS's exceedance probability of a storm model's stress sequence. Let $P_{ex,\Delta S,storm,RH}$ and $P_{ex,\Delta S,storm,AH}$ be $P_{ex,\Delta S,storm}$ calculated for real headings model and all headings model.

A storm sea sequence generated by a storm model with real heading model emulates the occurrence probability of sea state and relative heading angle. It is expected that $P_{ex,\Delta S,storm,RH}$ becomes close to $P_{ex,\Delta S}$ of the as-simulated stress sequence for the given route. Figure 6 and 7 show comparisons of $P_{ex,\Delta S,storm,RH}$ and as-simulated $P_{ex,\Delta S}$ for GCR and MTR routes. It is shown that the differences in $P_{ex,\Delta S}$ are in good agreement for both routes. These results demonstrate the capabilities of the storm model to emulate the long-term stress distribution experienced by ships which follow different routes. The results show an agreement of more than 85% in the stress long-term distribution. This is considered due to the improvement in the significant wave height long-term distribution corresponded to the as simulated sequence in 2.4.

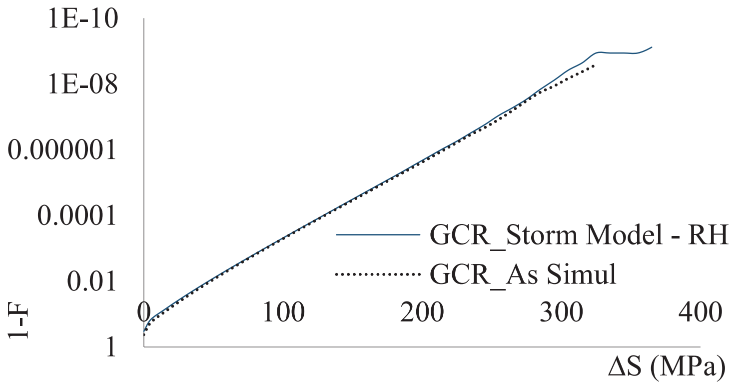

Figure 6: The comparison of $P_{ex,\Delta S,storm,RH}$ and as-simulated $P_{ex,\Delta S}$ for GCR route.

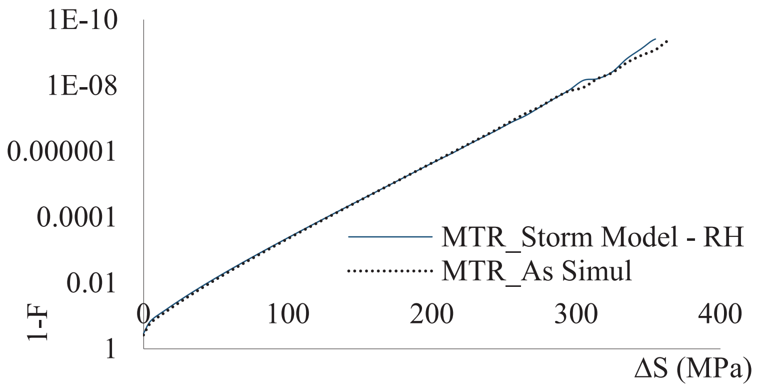

Figure 7: The comparison of $P_{ex,\Delta S,storm,RH}$ and as-simulated $P_{ex,\Delta S}$ for MTR route.

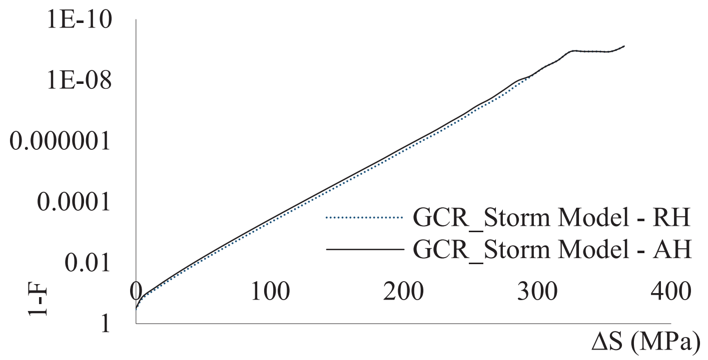

Figure 8: The comparison of $P_{ex,\Delta S,storm,AH}$ and $P_{ex,\Delta S,storm,RH}$ for GCR route.

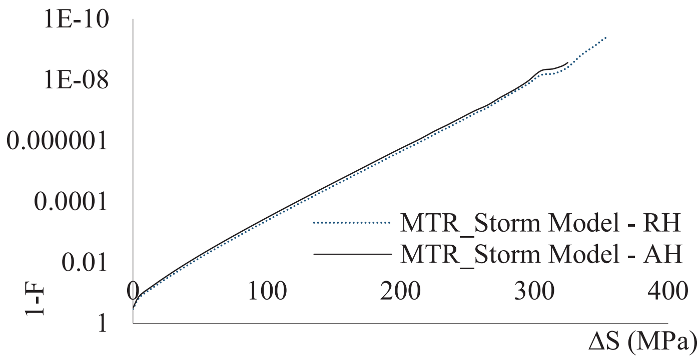

Figure 9: The comparison of P$_{ex,\Delta S,storm,AH}$ and P$_{ex,\Delta S,storm,RH}$ for MTR route.

Furthermore, Fig. 8 and 9 show the comparison of P$_{ex,\Delta S,storm}$ for all headings and real headings model in the GCR and MTR routes. It is noted in both cases the all headings model tends to slightly underestimate the stress response, while the difference remains nearly constant in the long-term prediction under the condition chosen. The above results show that the storm model configuration procedure, which was developed for cases without weather routing, is applicable to the case when routing is considered. Furthermore, the all headings angle tends to underestimate the long-term stress distribution under the condition chosen.

5. FATIGUE ASSESSMENT

5.1. Cumulative Fatigue Damage

Fatigue assessment of the butt welded joint on the upper deck of a 6000 TEU container ship is performed. The fatigue life under random loading is calculated based on linear cumulative damage (Palmer-Miner's rule) during 10 years,$D_{10years}$. The cumulative fatigue damages of the target welded joint $D_{10years}$ for a given ΔS sequence is calculated by the equation below:

$$D_{10years} = \sum \frac{n_i}{N_i}, \tag{2}$$

where n$_i$ is the number of stress cycles in i-th stress range block ΔS_i, N$_i$ the number of cycles to failure for ΔS_i, which is determined using DnV CN.30.7's curve I (for welded joints) (Det Norske Veritas, 2010). The thickness effect is not considered. The fatigue life L_f is estimated by Eq. (3) for each sequence.

$$L_f = \frac{10.0}{D_{10YR}} \quad (years), \tag{3}$$

Table 1: Comparison of the statistic L_f calculated by DnV CN. 30.7.

Route	GCR			MTR		
Sequence Model	Storm model RH	Storm model AH	As Simul.	Storm model RH	Storm model AH	As Simul.
D_{10YR}	0.3752	0.3149	0.3816	0.3324	0.2800	0.3537
L_f (year)	26.65	31.76	26.20	30.08	35.71	28.26

5.2. Fatigue Damage Results

The effect of the difference in the shipping route on S-N based fatigue assessment results on the North Pacific is examined. The stress sequences are generated by storm model. Additionally, the differences in the fatigue damage between the storm model and as simulated sequences in the GCR and MTR, assuming all headings and real headings model, are examined. The comparison of the statistic of the fatigue damage in 10 years, $D_{10years}$, are listed in Table 1.

It is noted in Table 1 that the differences in statistical properties of $D_{10years}$are about 13% smaller for vessels which follows weather routing, compared to those that follow a great circle route. This result appears accordingly to Fig. 4. This results clearly show the effect of the weather routing on the cumulative fatigue damage, extending the service life of the structure. Furthermore, Table 1 shows that the differences in $D_{10years}$are at most 6% in the cases of storm model, compared with those obtained on the as simulated sequence. These results are expected, as is shown in Fig. 6 and 7. As it is observed in Fig. 8 and 9, the stress exceedance shows a slight difference, between all headings and real headings model in both routes, GCR and MTR, and the difference on the cumulative fatigue damage is about 16% under the condition chosen. This means that the all headings model assumption tends to be conservative for the routes examined. However, this results cannot be generalized and more studies need to be conducted to clarify the effect of the weather routing and the headings model on the fatigue damage.

6. CONCLUSIONS

Fatigue damage assessment of the welded joint in the 6000 TEU container ship which sails on North Pacific routes is performed. Here are considered a great circle and a minimum time route. Stress sequences are generated by the adopting a storm model, assuming all heading and real heading model that emulates the occurrence probability of sea state and relative heading angle. S-N based fatigue assessment is performed. The followings are the results of this study:

- The storm model can successfully reproduce the (H_S, T_m, χ)sequences experienced by a ship that follows weather routing or not (in general with more than 85% of agreement). Additionally, the storm model procedure can reproduce the simultaneous long-term joint probability distribution of significant wave height and mean period for weather routing cases.

- The effect of the headings model on S-N based fatigue assessment is larger, compare to the difference in the estimated fatigue life due to the weather routing (is at most 16% under the condition chosen).

- Further research on the development of advanced wave load sequence model which can consider the elastic vibrations (whipping/springing) is needed.

7. ACKNOWLEDGEMENT

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