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Operational Methods for Ships in Waves—From Perspectives of Structure Health and Maneuvering Convenience

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Abstract: Based on the stress-strain data collected by a CSSMAS (container ship structure monitoring and analyzing system) onboard a container vessel, stress-strain responses of the ship's structure in high wave were analyzed and illustrated for the identification of reasonable safe course sections. Besides the ship's structure safety, the maneuvering convenience is also deemed as a main concern which influences the safety of vessels in heavy waves. In order to develop a comprehensive guidance in adverse weather condition, the basic requirements on maneuvering convenience for vessels in storm were further discussed. In combination of the two requirements, namely structure health and maneuvering convenience, a proposed operational method was thus developed, which was an amendment to the traditional navigational method for ship in extreme weather. At the end of this paper, an example of optimal course planning in bad weather was illustrated by using the operational method proposed.

Key words: Structural health, maneuvering convenience, extreme weather, operational method.

1. Introduction

Fatigue damage of ship's structure has been one of the main researching issues consistently attracting the attention of researchers in the shipping industry. Although these damages might not seriously lead to the ship's total loss, they are the main causes of expensive repairs and affect the normal operational availability. Therefore, many assessments and evaluation methodologies on the health of ship's hull structures have been developed [1]. Typical methodologies include the simplified assessment methods of hull strength mainly used by classification societies, stress spectrum analysis methods, design wave approach, and method of fracture mechanics [2]. Most of these approaches are mainly used at the ship's design and construction stage to ensure initially sufficient structural strength. However, ship structural fatigue is a complex subject, which is also influenced not only by structure form, constructional material, and even manufacturing process [3], but also by wave induced loads, ship's stowage in the daily business operation. Some of these factors also contain random characters.

Despite the measures taken for structure safety at the design and construction stage, the structural health problem needs also to be considered during the operation stage. The MSC (maritime safety committee) of the IMO (international maritime organization) have recommended the application of ship hull stress monitoring system since May, 1994. The purpose of this system is to confine the maximum stress on critical structural parts within a permitted range through continuous monitoring. Meanwhile, another purpose is to collect stress-strain data with a view to further analyse the performance of the structure in dynamic stress environment and then feed back to ship design and ship's maneuvering. However, limited by experimental conditions and data availability, few

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attempts have been made to analyse the real stress-strain data and feedbacks for ship's practical operation are also rare.

This paper reviewed ship's structure response to dynamic wave conditions by analyzing the stress-strain data collected from a CSSMAS (container ship structure monitoring and analyzing system) mounted on the training vessel of Yufeng owned by Shanghai Maritime University. Through real data analyzing and comparison with traditional navigational practices, a practical ship navigation method suitable for heavy sea conditions was presented as an operational guidance for navigators.

2. Researches on the Ship's Structure Health and Fatigue

Studies on ship's structure health and fatigue damage have gone through the phases from stress experiments in laboratory through stress modelling on computer to the combination of modelling and analysis of the stress data collected from real vessels. Using S-N Curves and Palmgren-Miner's linear cumulative rule, Munse [4] developed several approaches for fatigue damage calculation based on experiment data. These approaches allowed the estimation of pertinent sea states including significant wave height, dominant period and head direction, which affected the long-term stress distribution. By applying spectral method, XUE J. et al. [5] further incorporated other factors, including dynamic loads, vertical wave bending moment of longitudinal hull girder, horizontal wave bending moment, hydrodynamic pressure and inertial forces caused by cargo acceleration, into the fatigue damage calculation. Based on this sophisticated calculation methods and rigid body model, WU and Moan [6] developed a model of conventional load evaluation approach. The efficiency of the model was further tested on a 270 m long container ship.

For the overall ship hull strength assessment, Iijima and Moan [3] studied a consistent structural analysis procedure to estimate the global and local load effects. The procedure consisted of motion analysis, load evaluations. However, the accuracy of the structural analysis depended heavily upon the estimation of the wave load provided by the FE model of the whole ship. To improve the analysis accuracy, a calculation procedure for fatigue damage rate prediction of hull girders was presented by YAN et al. [7] by using stress data collected from an onboard SeaSense system. By integrating onboard estimation of sea states, this procedure conceptually illustrated how the system was used to deduce decision-making with respect to the accumulated fatigue damage in the hull girder. Tremendous studies [8, 9] including the above mentioned ones have focused on modeling the stress and fatigue on ship's hull structures for the evaluation of safe design and safe construction purposes. However, there were rare researches which focus on the model of real stain-stress data to examine the traditional operation methods of ships and to feed back to the ship's practical operation.

3. Experiment on Stress Data Collection in High Waves

3.1 Location Arrangement of Stress Sensors

The CSSMAS was a stress-strain monitoring system with basic function of structural health assessment for container ships. The sensors of this system consisted of position sensors, ship motion sensors and stress-strain sensors. The locations of stress-strain sensors play a significant role on the quality of data used to reflect the strain state of vessels. To improve the data quality, the location arrangements of sensors in this system were carefully designed and evaluated [10]. The pre-considerations on the position arrangement included the followings: main reasons leading to the structure fatigue on container vessels, the structural characters, and the basic principles from classification societies on location selection for stress assessment. Following these principles, the sensors' position arrangements were determined as follows and shown in Fig. 1. These arrangements intended to meet the requirements of both the static structural stress assessment and dynamic structural stress assessment for ships' operating at sea.

Locations of stress-strain sensors of the CSSMAS:

(1) Points on the cross-section of the longitudinal girders ranging from the perpendicular with distances of 1/4L, 1/2L, and 3/4L (L: length of the ship) to the rudder stroke. These points include S1, S3, S6 and S9;

(2) The conjunction points between the deck longitudinal, side longitudinal, bottom longitudinal and strong transverse frameworks of the ship's hull. Typical points are S2 and S4;

(3) The corners of the hatchway such as point S7 and S8.

3.2 The Experiment in High Waves

To reveal the stress-strain response of ship's hull to waves, an experiment was carried out on YUFENG in the vicinity around the position of 31°48′N,123°43′E on 19th April, 2010. Because the intersection angle between ship's course and the running direction of the sea wave has close relation to the wave induced loads on the hull, the vessel was keeping changing its courses at an interval of 5 degrees during the experiment for the collection of comprehensive responses under given sea and loading conditions. For each course, it was kept for about 3 minutes in order to collect stable strain response. The total time span of this experiment was 1 hour and 3 minutes. Thirteen experimental courses were tested. The course errors were about ±0.5° which was within the limits of the IMO conventional requirements. See Table 1 for data recording and Fig. 2 for the process illustration of the experiment.

4. Stress-Strain Data Analysis

4.1 The Course-Stress Evaluation Methodology

For the convenience of ship's operation and data analysis, the intersection angle between the ship's course and the wave crest top line was defined as the encounter angle in this study. Therefore, the effective encounter angle has a range scale ranging from 0 to 90 degrees. The experimental data recorded in table 1 show the typical encounter angles and the relevant stress data available collected by the CSSMAS. The sampling cycle of the stress-strain data in the CSSMAS was set at 1/8 second, which was precise enough to measure the response of hull structure to the wave induced load whose cycle period was about 8 to 10 seconds. So, the stress data thus collected could be used to reflect the variation of stress on the hull, which could be deemed as the direct reflection of the

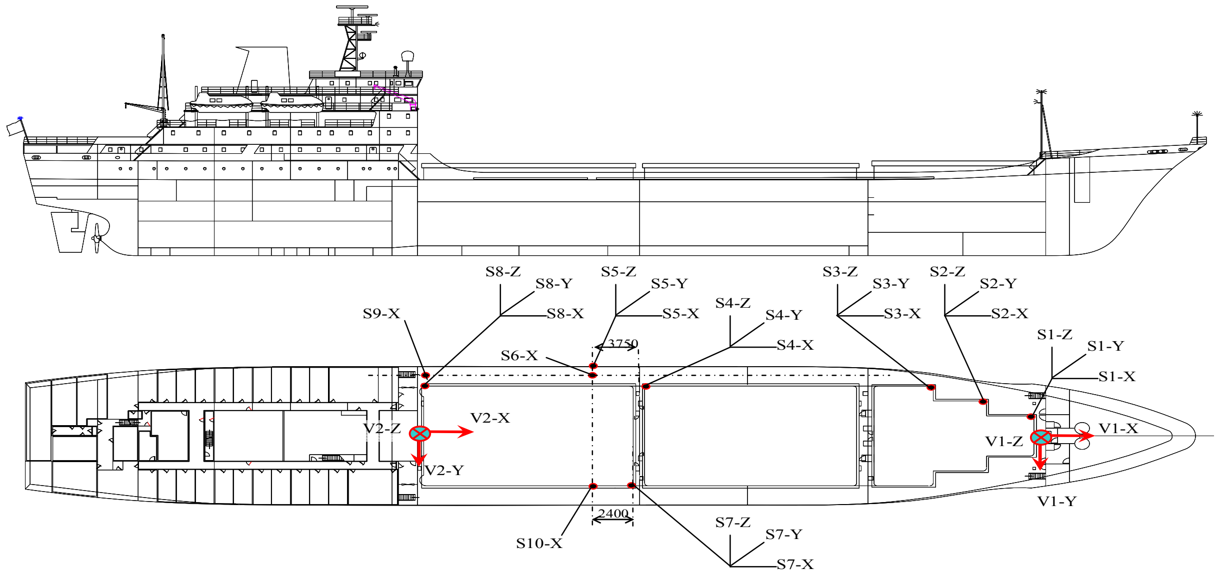
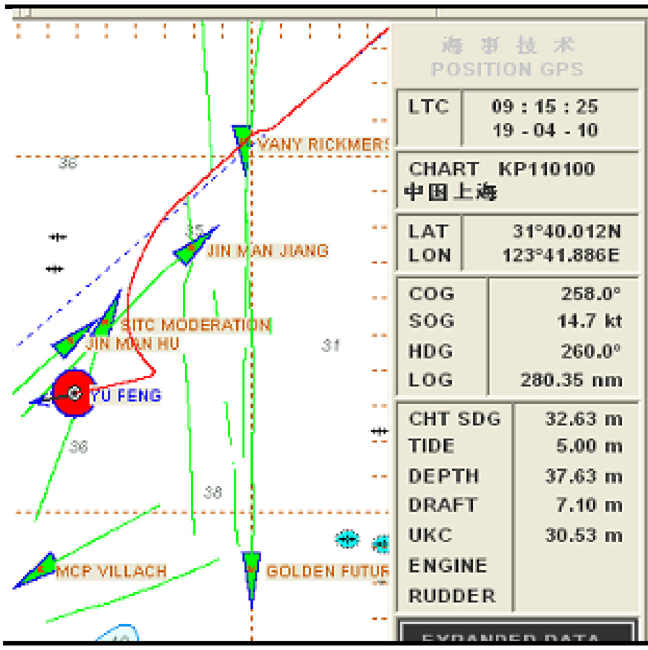


Fig. 1 CSSMAS sensors layout plan.

Table 1 Experimental data recording.

Course (°)	Start time (hh : mm : ss)	End time (hh : mm : ss)	Direction of the wave crest line	Intersection angle
225	07 : 40 : 00	07 : 43 : 15	235	10
220	07 : 44 : 40	07 : 47 : 50	235	15
215	07 : 50 : 30	07 : 53 : 30	235	20
210	07 : 54 : 40	07 : 57 : 40	235	25
205	07 : 58 : 50	08 : 02 : 50	235	30
200	08 : 03 : 30	08 : 06 : 30	235	35
190	08 : 13 : 00	08 : 16 : 00	235	45
180	08 : 17 : 50	08 : 20 : 50	235	55
170	08 : 22 : 10	08 : 25 : 10	235	65
160	08 : 27 : 00	08 : 30 : 00	235	75
150	08 : 31 : 30	08 : 34 : 40	235	85
140	08 : 35 : 30	08 : 38 : 30	235	95
130	08 : 40 : 15	08 : 43 : 15	235	105



- Basic conditions of the experiment:
- Sea wave height: 1.5 m~2.5 m,
- Sea wave direction: 325°,
- Wind force: 7 in Beaufort scale,
- Ship speed: 10 knots,
- Ship length: 139.8 m,
- Ship width: 20.8 m,
- Ship's gross tonnage: 10,134 t.

Fig. 2 The experimental track of the vessel.

strain state of the hull in sea waves. At least 1,440 strain states for each experimental course were recorded according to the system sample period and the lasting of time on each course. From the practical operation point of view, the research focus was on the identification of the optimal available course sectors among the 13 courses in Table 1.

Container vessels normally possess relatively small block coefficients especially for those of the large container ships. Affected by the sea waves, these vessels normally suffer significant strain on parts in the middle of the ships [11]. The stress-strain and fatigue will be more serious when ships are in hog or sag states encountering simultaneously high waves with wave length equivalent to ships' length. These kinds of heavy sea waves are quite frequent during summer time of Indian Ocean and winter time in North Atlantic Ocean. Therefore, the structural health monitoring and evaluation for those kinds of ships are essential. To identify the optimal courses for ships operating in waves, it is necessary to develop an applicable assessment measure used to evaluate the stress states against different ship's courses. Through ship model test, a comprehensive stress assessment approach for the identification of minimal stress state among different courses under the same sea conditions was developed:

$$\mathrm{Val}_{(\tau)} = \sum_{i=1}^{I} \mu_i \frac{\sum_{n=1}^{N} S_{in}}{N} \quad (1)$$

where:

T: encountering angle;

I: number of sensors;

μ_i: weight of the sensor i;

N: number of the data sample for sensor i;

S_{in} : stress value of sensor i.

Val(T) is a general stress state indicator for a particular ship's course. The parameter μ_i is used to adjust the function for the fitness of ships with different block coefficients. Experimental result shows that function 1 could be used as an indicator of the evaluation of general stress state of a ship under the same sea and weather conditions.

4.2 Stress Data Statics and Analysis

Based on function 1, the stress data on different courses were processed and the resultant indicators were shown in Fig. 3. If stress was the only parameter used for the identification of optimal courses, Fig. 3 showing the best courses range was the encountering angles with a range of 30° to 75°. Both the less encounter angles from 0° to 30° and the larger ones from 75° to 90° would lead to relatively remarkable stress response on the ship's hull.

Although the stress of ship's hull is one of the essential considerations for safety purpose, there are also other factors that call for the attention of the navigators. These factors include especially ship's maneuvering convenience and the suitability of the working environment for the seafarers and ship-borne equipment. In this regards, to effectively mitigate the rolling and pitching of vessels in rough weather is the main approach for reaching the requirement of these factors mentioned above. The rolling angle of a vessel is normally given as:

$$\theta = \frac{\alpha}{1-\left(\frac{t_\theta}{T_\theta}\right)^2} \quad (2)$$

where:

α : wave slop angle,

$t_\theta = \dfrac{\lambda}{V + V_1 \sin\beta}$: encountering period between a ship and waves, λ: the wave length, V: wave velocity, V_1: ship velocity, and β: Encounter angle.

$T_\theta = C_O \cdot B\sqrt{GM}$: rolling period, C_0: coefficient of rolling, B: ship's width, GM: initial stability height.

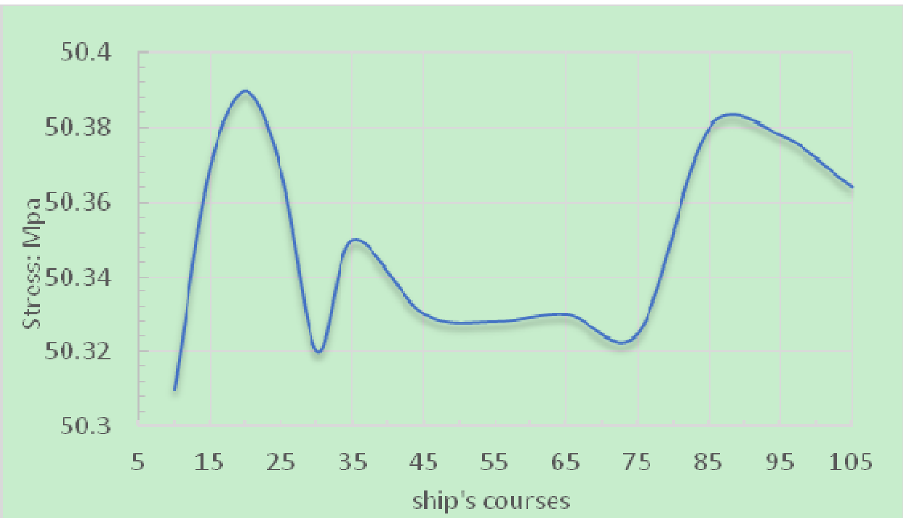


Fig. 3 The stress under different experimental courses.

Eq. (2) shows that the rolling amplitude of a vessel is mainly determined by the value of expression $(t_\theta/T_\theta)^2$. Therefore, the process of the expression $(t_\theta/T_\theta)^2$ in approaching the value of 1 corresponds to the process of θ getting larger and larger. When the two periods tend to be the same, ship's synchronous rolling will happen, jeopardizing the vessel's safety into extreme dangerous situation. Normally, it is required that the expression of (t_θ/T_θ) should have a value range of [0.7, 1.3]. Navigators, therefore, need to operate vessels to avoid the ratio falling into this value range. Through careful examination of Eq. (2), it is found that α is a constant, B and GM could be a fixed value under a specific loading condition, and λ and V could also be deemed as constant during a relatively short time period. Hence, the rolling angle θ is solely determined by parameters β and V_1. However, the effect of the variation of speed V_1 on the angle θ is also neglectable under a given propeller revolution rate. Hence, the above analyses lead to the conclusion that the rolling angle of a vessel under a specific sea condition is significantly influenced by the encounter angle β. So a function exists.

The ship's pitching should also be maintained in a reasonable range for maneuvering purpose. That is because the pitching amplitude is the main cause of deck washing, slamming and idle state of the main engine. In practical operation, pitching angles are affected by the variation of β. Therefore, a proper β is also necessary in order to mitigate pitching.

Based upon the above discussion, a proper encounter angle should be kept in order to maintain the ship's maneuvering convenience. Fig. 4 gives the integrated influence indicator [12] θ′ for assessing ship's rolling and pitching influence on the health state of a ship's structure against its encounter angle β. The curve may vary slightly for different ships. The point c stands for the optimal sailing state with minimum rolling and pitching. Points a and b correspond to the minimum and maximum encounter angles permitted for the safety of ship. And d means the extreme amplitude that a vessel could undertake.

5. Identification of Reasonable Encounter Angles

According to Figs. 3 and 4, proper encounter angles are those which could ensure both the stress on the hull, and rolling and pitching amplitude to reach optimal states.

When a relatively small encounter angle is applied, the waves will be a beam of the ship. This ship's position should be avoided. On one hand, ships will have serious rolling, which corresponds to the value of θ′ between O and the point a in Fig. 4. On the other hand, although stress at the relatively small encounter angle of 10 is weak as shown in Fig. 3, the other encounter angles around 10, will lead to remarkable stress load on the hull, making the changing of course a dangerous action. Therefore only a narrow applicable course sector is available. However, even if ship's course could be kept within this narrow sector, the serious rolling aroused by these courses could also lead to other manoeuver problems such as cargo shifting, improper working condition for both seafarers and navigational equipment, and even the capsizing of the vessel [13]. So, relatively small encounter angles are not applicable.

Running against or before the seas is also not the best practices, which is, however, commonly adopted in high waves operation [14]. This could be seen in Fig. 4 for β with value ranging from b to $\pi/2$. The stress performance thus induced is also not in an optimal state as shown in Fig 3 between 85 and 105. Normally, a ship will experience large angle pitching when heading on the waves in gale. Large angle pitching is usually the root of serious sliming and the state of propeller running out of water, which should be avoided during the operating of ships. So this range is also not the desired rang of practical encounter angles.

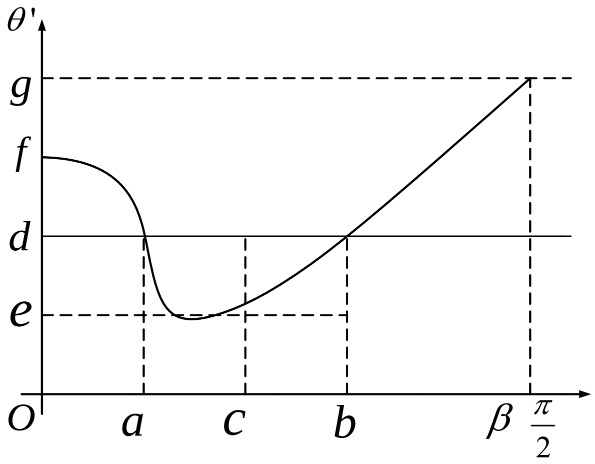


Fig. 4 The amplitude curve of ship's rolling and pitching against wave direction.

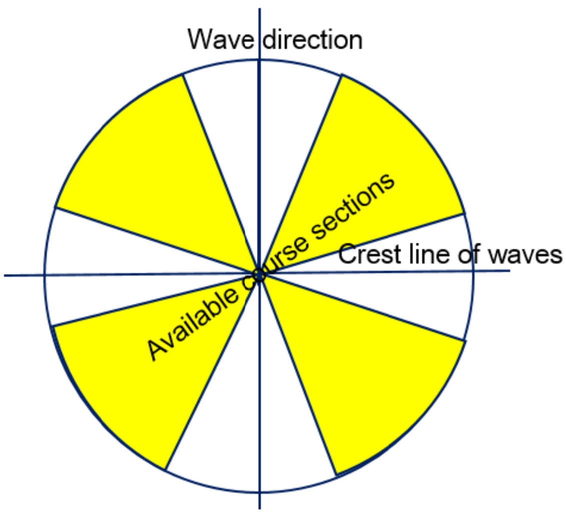


Fig. 5 Selectable course sections while waves abeam ship's course.

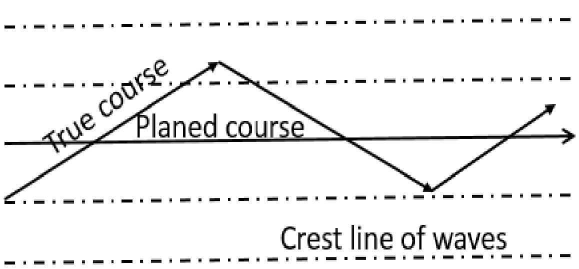


Fig. 6 Route patterns for waves abeam of ship's course. State of propeller running out of water, which should be avoided during the operating of ships. So this range is also not the desired range of practical encounter angles.

The ideal value range for encounter angles should be the common areas between Figs. 3 and 4, where both the motion of rolling and pitching and the stress on vessel's structure are relatively weak. Let T be the perfect set for encounter angles for vessels in gales and storms. We have the results as following.

In real practices, the optimal course is the one selected from the set of T according the length of a ship, the loading and environmental conditions.

If strong storm is met, it is recommended keeping course within a specific range of courses instead of on a specific direction [15], which allows the protection of the main engine and ship's rudder from damages. In this case, T is the ideal course range.

To reveal the course selection in high sea states, a most adverse sea condition was selected as an example. It was the situation that the planed course was parallel with the crest top line of the waves. Figs. 5 and 6 gave the available course sections and route patterns. The main point was to ensure the encounter angle being a specific angle within the set of T.

6. Conclusions

Owning to continuous expansion in ship's size, structural fatigue becoming more and more serious, this paper angled to provide feedbacks to the ship's operational side from the ship structural health perspective through the using of stress-strain collected by the CSSMAS. To reveal the actual strain response of ship's hull to the dynamic wave load, an experiment was carried out and stress-strain data were collected under different encountering angles. The courses evaluation against stress revealed that the best encountering angles were those with a value range of 30° to 75°. The examination of this value range against the ship's maneuvering convenience further showed that the optimal value range of encounter angles was the common value ranges, which could ensure both the motion of rolling and pitching and the stress on vessel's structure was relatively weak. The generated value ranges proved that the navigation method in this paper was an amendment to the traditional navigational methods for vessels in high waves. The example of course planning under most adverse sea and wave condition at the end of this study showed the availability of this proposed navigation method, which could serve as a general guidance for mariners operating in high waves.

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References

[1] Fricke, W., and Kahl, A. 2005. "Comparison of Different Structural Stress Approaches for Fatigue Assessment of Welded Ship Structures." *Marine Structures* 18 (7-8): 473-88.

[2] GUO, B. J., Bitner-Gregersen, E. M., SUN, H., and Helmers, J. B. 2016. "Statistics Analysis of Ship Response in Extreme Seas." *Ocean Engineering* 119: 154-64.

[3] Iijima, K., YAO, T., and Moan, T. 2008. "Structural Response of a Ship in Severe Seas Considering Global Hydroelastic Vibrations." *Marine Structures* 21 (4): 420-45.

[4] Munse, W. H., Wilbur, T. W., Tellalian, M, L., and Wilson, K. 1982. "Fatigue Characterization of Fabricated Ship Details for Design." SSC Report N. 318.

[5] XUE, J., Pittaluga, A., and Cervertto, D. 1994. "Fatigue Damage Calculation for Oil Tanker and Container Ship Structures." *Marine Structure* 7: 499-535.

[6] WU, M., and Moan, T. 2005. "Efficient Calculation of Wave-Induced Ship Responses Considering Structural Dynamic Effects." *Applied Ocean Research* 27 (2): 81-96.

[7] YAN, X. S., HUANG, X. P., HUANG, Y. C., and CUI, W. C. 2016. "Prediction of Fatigue Crack Growth in a Ship Detail under Wave-Induced Loading." *Ocean Engineering* 113: 246-54.

[8] Temarel, P. et al. 2016. "Prediction of Wave-Induced Loads on Ships: Progress and Challenges." *Ocean Engineering* 119: 274-308.

[9] Kim, M. H., Kim, S. M., Kim, Y. N., Kim, S. G., Lee, K. E., and Kim, G. R. 2009. "A Comparative Study for the Fatigue Assessment of a Ship Structure by Use of Hot Spot Stress and Structural Stress Approaches." *Ocean Engineering* 36 (14): 1067-72.

[10] Akpan, U. O., Koko, T. S., Ayyub, B., and Dunbar, T. E. 2002. "Risk Assessment of Aging Ship Hull Structures in the Presence of Corrosion and Fatigue." *Marine Structure* 15 (3): 211-33.

[11] ZHOU, F. 2017. "Parameters Estimation and Evaluation for the Probability Density Function of Structural Fatigue Stress of a Container Vessel." *Journal of Shipping and Ocean Engineering* 7: 1-8.

[12] Butler, R. W., Machado, U. B., and Rychlik, I. 2009. "Distribution of Wave Crests in a Non-gaussian Sea." *Applied Ocean Research* 31(1): 57-64.

[13] Jacobi, G., Thomas, G., Davis, M. R., and Davidson, G. 2014. "An Insight into the Slamming Behaviour of Large High-Speed Catamarans through Full-Scale Measurements." *Journal of Marine Science And Technology* 19 (1): 15-32.

[14] Frangopol, D. M., Strauss, A., and Kim, S. 2008. "Bridge Reliability Assessment Based on Monitoring." *Journal of Bridge Engineering* 13 (3): 258-70.

[15] Deco, A., and Frangopol, D. M. 2015. "Real-Time Risk of Ship Structures Integrating Structural Health Monitoring Data: Application to Multi-objective Optimal Ship Routing." *Ocean Engineering* 96: 312-29.