Cracking Propagation Prediction Methodology Applied for a Bulk Carrier

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This paper presents a methodology of evalutation aiming to predict the crack propagation in ships in the case of ductile materials under fatigue load This methodology, based on linear elastic fracture mechanics concepts, is the result of a literature review from the continuum mechanics to be applied in the naval area. The resulting mathematical sequence is based on energy theory associated to preexisting crack applying Paris's Law relating the propagation rate of the crack size, stress variation and number of cycles until it reaches a critical size. The application of a stress correction factor is considered due to the hardening that provides plasticity in the region of crack. To demonstrate the proposed methodology application in shipbuilding area a model of bulk carrier was used. The development of this paper is expected to contribute with a mathematical model that permits to predict crack propagation under fatigue action.

Keywords: *Fracture mechanics, fatigue, crack propagation, ships, naval.*

1. INTRODUCTION

Ship structures such as vessels and platforms are vital tools of the oil industry, being responsible for extraction, storage, transportation, and even in some cases refinement of crude oil. The high added value inherent to those vessels demands them to be in constant use, once any significant damage in a ship can cause a big loss in the whole production chain, which involves cargo damage, pollution and even the safety of the offshore crew. Ship design relies on technical, economic and environmental factors, that when not fulfilled, could lead to a fracture of the hull. One of the most common causes of fractures are cracks. Fatigue, according to [1], represents the progressive and located weakening as a result of dynamical loads, which after a certain number of cycles may result in the failure of the material.

The hull of a ship is subjected to several kinds of loads, such as alternate stress of waves, vortex induced vibrations and wind loads. Fatigue cracks may appear on the surface or within the material, and can even be generated in the metal forming processes, heat treating, welding and others that are largely used in the shipbuilding industry [1].

According to [2] the crack growth prediction in ships requires the following steps:

- Analysis of structure and structural details for definition of critical points;
- Stress analysis of the structure to assess the intensity factor in the crack;
- Data collection regarding previous recorded stress on the crack;
- Determination of crack propagation properties regarding growth rate in welding materials and heat affected zones, if relevant to the crack;
- Integration of crack growth, either cyclical or by cycle batch regarding small increment.

This effect of crack birth, growth and propagation is perhaps less evident in the case of other materials commonly used for small boats, such as wood or fiber reinforced plastics. These non-metallic materials, often snobbed when dealing with large shipbuilding, are supported by studies on the evaluation of the agging effect of salt water [3,4] and are getting back on track in considerations of unexpected advances in manufacturing [5] and their overall properties. These reinforcements might involve nanofibers [6], synthetic [7], natural [8, 9] or hybrid fibers [10, 11], representing a valid solutions for specific applications [12].

Focusing on metals and the problems occuring when cyclic loads are applied, within the study of propagation of cracks there is a size characterized as critical, in which the crack does not propagate any longer, but the material fails. When the crack is still small, it is important to oversee the propagation. Most times, the crack propagates by stress concentration in the origin point.

Finite element methods are tools that can be used to predict fatigue life, as showed in [13-15] which compared the results of experiment with numerical simulation. Thus, the detailed design should aim at reducing the stress concentration on the material. The stress concentration reduction implies in the crack propagation deceleration [2]. Therefore, this paper analyses the behaviour of cracks in ship structures, and aims at quantifying the time a crack stays in the hull as long as it does not cause damage in the vessel.

The method used in this paper is based on the fracture mechanics theory applied in the shipbuilding field regarding the global wave load analysis of stress. Dynamic loads caused by waves are obtained by shipbuilding standards of classification societies.

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2. FRACTURE MECHANICS

The common characteristic of steels used in shipbuilding is that they are ductile. [16] tells that a ductile material is characterized by its capacity to absorb energy before its fracture by plastic deformation. The fracture process occurs by nucleation, propagation and finally failure of the material.

The failure can be defined as the separation of the material in two or more parts, and the fracture mechanics study relies on the hypothesis of a model of the continuum mechanics, where the microstructure can be disregarded, according to [1].

There are three basic situations in engineering that differ by the way the load is applied in the crack. The crack separation modes are shown in Figure 1.

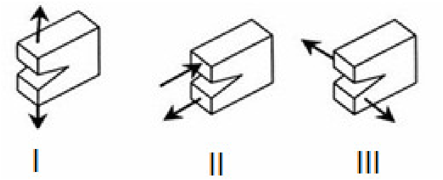

Figure 1. Load modes in cracks

Mode I is called opening mode, where crack propagates by forces normal to the plane of the crack. The mode II is called sliding mode where the crack is caused by shear stress parallel to the plane of the crack. The mode III is the out-of-plane shear crack in which the load is parallel to the plane of the crack and to the crack front. The modes II and III require a much deeper and complex analysis than that of the mode I, which will be used in this paper.

An expression was achieved in [17] for calculating the maximum stress in a crack, as shown in (1):

$$\sigma_{\max} = 2\sigma_c \sqrt{\frac{a}{\rho}} \tag{1}$$

Where $\sigma_{\max}$ is the maximum stress that can be applied to the material, σ_c is the material-dependent critical stress, a is half of the crack's length and ρ is the radius of the crack edge. Rearranging (1), the constants components are in one side, creating a new constant (2):

$$\sigma_c \sqrt{a} = 0.5\sigma_{\max}\sqrt{\rho} = K \tag{2}$$

K is defined as the stress intensity factor.

[18] found another similar constant (2), but he achieved the same results using energy methods. He noticed that a minimum energy level can foretell the material failure of ductile components under the consideration that there is an energy increase in the crack. This increase is expressed as (3):

$$U - U_0 = -\frac{\pi\sigma^2 a^2}{E} + 4a\gamma_s \tag{3}$$

where U is the potential energy of the plate with the crack and U_0 is the potential energy of the plate without the crack. σ is the stress, a is half of the crack's length, E is Young's modulus and γ_s is the superficial energy of the material. To obtain the equilibrium equation, one must differentiate the previous equation equaling to zero.

$$2\gamma_s = \frac{\pi\sigma^2 a^2}{E} \tag{4}$$

The second derivative, (5), defines the nature of the equilibrium, and in this case, being negative, implies an unstable condition. In other words, the crack will propagate until fracture.

$$\frac{\partial^2 U}{\partial a^2} = -\frac{2\pi\sigma^2}{E} \tag{5}$$

(4) can be rearranged in a way to leave the crack propagation in function of its characteristics and of the stress. Considering that it is a plane stress and biaxial condition: $\sigma_Z=\tau_{ZX}=\tau_{ZY}=0$

$$\sigma\sqrt{\pi a} = \sqrt{2E\gamma_s} = \text{constant} \tag{6}$$

$$K_C = \sigma\sqrt{\pi a} \tag{7}$$

where K_C is the critical value of K. The critical stress intensity factor can be used as reference in the selection of material and for mode I cracks, it is known as K_{IC}:

$$K_{IC} = Y\sigma\sqrt{\pi a} \tag{8}$$

where Y is a constant regarding the place of the crack in the plate. The value of Y is one for a crack in the middle of an infinite plate and Y=1.12 at the edge of a semi-infinite plate.

3. PARIS' LAW

The fatigue theory was constructed on a hypothesis that enables the calculation of structural geometric lifespan from tests using two parameters: the nature of stress fields next to the crack and the variation of the field. These parameters are used to assess the crack length growth in the material.

The samples have cracks in which geometry and the load are symmetrical to the plane of the crack.

The fracture toughness is related to the load and geometry of the material next to the crack. So, as the load and the shape of the crack changes, the instantaneous value of K changes as well and it is the most relevant parameter that describes the growth of the crack [19]. The stress intensity factor variation can be described as (9).

$$\Delta K = Y\sigma\sqrt{\pi a} \tag{9}$$

$\Delta\sigma$ is the load variation at each cycle.

Tests were made by [20] with several materials and showed that the rate of propagation of a crack is determined by the load variation, as shown in Figure 2. Also [13] compared experimental tests and numerical simulation applying Paris' Law for crack growth propagation and the results have showed to be similar, which indicates the validation of the method.

The region I is the crack nucleation stage, a microscopic behavior of the material. Some of it is caused by welding and happens not only on the surface but also within. The region III is where the failure happens, when the crack size has reached a critical value. The fracture is generated by: load, crack's length and material toughness.

The region II is the stage of crack propagation and has been more extensively studied. The main factor as well is the load difference, but the welding joint geometry and cracks initial length influences in the fatigue lifespan. In welded structures, the fatigue cracks usually represent 90% of the fatigue lifespan. This area can be described by the following expression:

$$\frac{\partial a}{\partial N} = C\left(\Delta K\right)^m \tag{10}$$

Where $\partial a/\partial N$ is the crack´s growth rate, C and m are a material constant, defined by [21].

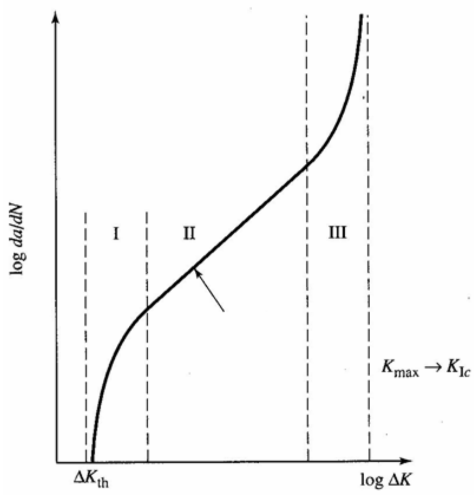

Figure 2. Paris' Law

Using (9) in (10) and integrating, the number of cycles until failure, N_f, can be achieved:

$$N_f = \frac{2\left(a_c^{\frac{2-m}{2}} - a_i^{\frac{2-m}{2}}\right)}{(2-m)C\left(\Delta\sigma\sqrt{\pi}\right)^m} \tag{11}$$

Where a_c is the critical length of the crack, a_i the initial length where the crack starts to propagate by the load difference $\Delta\sigma$.

4. ELASTIC AND PLASTIC DEFORMATION OF METALS

Most metallic materials can hold elastically deformation until a limit, beyond this limit, the Hooke's Law is no longer applicable and the material can not return to its initial configuration. Such will happen because of break and renewal of atomic bonds.

At the beginning of the plastic deformation, a correction can be made in the stress and strain values to consider the occurrence of strain hardening in the material. These values are called real stress and strain (12).

$$\bar{\sigma} = A\bar{\varepsilon}^n \tag{12}$$

Where $\bar{\sigma}$ is the real stress, A is a material constant, $\bar{\varepsilon}$ is the real strain and n is the strain hardening parameter.

The strain hardening parameter determines how the material behaves regarding strength, hardness and strain. As n increases the distance between yield point and ultimate strength point also increases, causing a greater deformation in the material [22].

The values for A and n are not obtained by tensile tests. The real stress depends on the deformation by Hooke's Law, (13), and follows (14) [14].

$$\sigma = E\varepsilon \tag{13}$$

$$\bar{\varepsilon} = \ln\left(1+\varepsilon\right) \tag{14}$$

Where E is elastic modulus. Applying (13) into (14) gives (15).

$$\bar{\varepsilon} = \ln\left(1+\frac{\sigma}{E}\right) \tag{15}$$

Applying (15) into (13), the real stress applied to the material is presented in (16).

$$\bar{\varepsilon} = \ln\left(1+\frac{\sigma}{E}\right) \tag{16}$$

5. STRESS ON SHIPS

Both ships and ocean platforms are exposed to several kinds of loading. The structure holds its own weight, cargo, goods or consumable, environmental loads and waves. To ships, currents and waves are the majors contributors in the ships overall load in the structure.

The fatigue analysis in maritime structures will be represented by the stress generated by static and dynamic loads. Static loads occur in calm sea, and dynamic loads are generated by the occurrence of waves [23].

To stress calculations applied in a ship, based on the Classification Society Manual from [24], equations that define the bending moment acting in the ship in sagging and hogging where obtained.

Hogging, as can be seen in Figure 3, is the situation that the crest of the wave is at midship, making efforts of compression at the bottom and traction at the deck.

Figure 3. Hogging and sagging, respectively

In the sagging condition, in the other side, the midship is at the trough of the wave, the crests are under the bow and stern, as can be seen at the right of Fig. 3. This way, at midship, the bottom is under traction and the deck under compression.

Supposing that the wave passing through the ship has the same length as the ship, maximum hogging and sagging bending moment will be generated. Each passage of the wave, therefore, will be considered as one cycle of stress, in which the maximum and minimum stress are the hogging and sagging stress, respectively.

The transversal section in analysis is the midship section, because is in this region where the greatest moments occur.

For the application of the [24] rules described, three relationships must be satisfied:

$L/B \geq 5$;
$BD \leq 2.5$ and
$C_B > 0.7$

Where L is the length, B is the beam D is the depth and C_B is the block coefficient which can be determined by (17).

$$C_B = \frac{\nabla}{1.025LBT} \tag{17}$$

Where ∇ is the volume of the hull at a draught T.

The bending moments in calm sea are found by (18) and (19), being M_{ST} and M_{SA} the bending moments in calm sea for sagging and hogging, respectively. The unit is [kNm].

$$M_{ST} = -0.065 C_W L^2 B \left(C_B + 0.7\right) \tag{18}$$

$$M_{SA} = C_W L^2 B \left(0.1225 - 0.015 C_B\right) \tag{19}$$

Where C_W is the wave coefficient that depends on the length L in Table 1. Bending moments on waves can be found by (20) and (21) below, where M_{WT} and M_{WA} are bending moment in seas with waves for sagging and hogging condition, respectively.

$$M_{WT} = -0.11 \alpha C_W L^2 B \left(C_B + 0.7\right) \tag{20}$$

$$M_{WA} = 0.19 \alpha C_W L^2 B C_B \tag{21}$$

Table 1. Wave Coefficient

L	C_W
$L \leq 100$	0.0792L
$100 < L \leq 300$	$10.75 - [(300-L)/100]^{3/2}$
$300 \leq L \leq 350$	10.75

Where α is a coefficient related to navigation conditions, being 1 for open sea and 0.5 for harbor regions. The values of stress are the relation between bending moment and transversal section modulus. The section modulus is a geometric property of the analyzed section, and can be found by (22), being the ratio between the inertial moment of area I in relation to y axis and the coordinate y of the centroid. Following the classification societies rules, the minimum section modulus Z must be estimated by (23) in [cm³]:

$$Z = \frac{I_y}{Y} \tag{22}$$

$$Z \geq \frac{c_w}{f_1} L^2 B \left(C_B + 0.7\right) \tag{23}$$

Where f_1 is a constant depending on the yielding stress, σ_Y of the material. The relation between bending moments and stress are given by (24).

$$\sigma_{T,A} = \frac{\left|M_S + M_W\right|}{z} 10^3 \tag{24}$$

The consideration is that the height of the wave that acts on the ship is the critical wave height H, that can be found by (25) for ships with $220 < L_{PP} \leq 305$ meters.

$$H = \left[4.5 L_{PP} - 0.007 L_{PP}^2 + 103\right] \times 10^{-2} \tag{25}$$

6. STRAIN HARDENING EXPONENT CORRECTION

The strain hardening exponent presented in (16), as mentioned before, changes the yield and ultimate strength point during the application of the load. By using the strain hardening theory on the equations of stress on the ship, one can consider that from the elastic the strain reached a plastic condition, with irreversible deformations, which is what a crack is. In this work it is suggested that the exponent will not only be affected by strain hardening but also by several other cumulative factors that deteriorate the material, increasing the stress to a real value.

This new exponent will be defined as n^*, and will be called deterioration exponent, given in (26):

$$n^* = K_E \times K_V \times K_S \times n \tag{26}$$

Where K_E, K_V, K_S are related to ageing, vibration of machinery and welding, respectively.

Aging of material happens regardless of environment and it is time dependent. The carbon and nitrogen atoms diffusion by the plastic deformation are the main factors. Yielding stress increases but the ductility is affected, losing stretching capacity [25].

Regarding vibration in the hull, is well known that the fatigue occurrence on ships is also due another factors beside sea waves. Engines, motors and other equipment in the ship generate vibration and are source of cycles of stress in the hull.

The welded area affects directly the microstructure and plasticity of the material since the welding process creates the heat-affected zone. Even with heat treatment, some effects of the zone persist.According to [26], the microstructure has fundamental influences on fatigue crack propagation.

The contribution of each one of these factors multiplied by the strain hardening exponent will correct the stress difference, increasing or decreasing it, and it can be applied in the crack length growth propagation.

7. METHODOLOGY APPLICATION

To apply the presented methodology the bulk carrier JRS MERKUS was chosen. Data of the ship was published in [27]. The main dimensions are shown in Table 2.

The route of the ship is considered to be non-restrictive, that is, it does not have restrictions related to the distance from the coast and can be subjected to any kind of environment. Another consideration is that the ship does the round-trip fully loaded.

Table 2. Ship Main Characteristics

L_{PP}	103.8 m
B	18.2 m
T	7.1 m
C_B	0.83

The moments were calculated for sagging and hogging, and the results are showed in Table 3.

To calculate the stress it is necessary to find the midship section modulus. Based on images of the ship was estimated the midship section, with these dimensions and considering the thickness of the plates as 0.025 m, the midship section found is 11,438,707.30 cm³. This value is greater than that required by [24] rules in (23), which is 1,844,636.90 cm³.

Table 3. Results of Bending Moment Calculations

Condition	Mso [kNm]	Mw [kNm]
Sagging	-156048.111	-264081.419
Hogging	172680.69	247448.84

The determined stress by (19), as well as the cor–rection to find the real stress by (18) are in Table 3. It was considered in this case that the material suffers har–dening influence, and the constant A for SAE1020 steel is 0.22.

The hardening coefficient was corrected with the factors of equation 33. At this point, because of the lack of data and research about the topic in marine area, it is assumed that each corrective factor has an influence of 20% in the steel plasticity. The corrected coefficient passed from 0.22 to 0.11, and the results are shown in Table 4.

Table 4. Ship Main Characteristics

Condition	Stress [MPa]	$\Delta\sigma$ [MPa]
Sagging	- 645.63	1291.26
Hogging	645.63	

To apply (11) is used with the values of C and m for ferritic-perlitic steel. The number of cycles found is 233.79.

To transform thes cycles in time, Boston was considered as the port of origin of the ship and Rotterdam as the port of destination . The route can be completed in 10 days with the service speed of 13 knots. The round trip would take 20 days. The sea environment to which the ship would be exposed is the North Atlantic, and its wave spectrum can be considered as a non-restricted route of service [19].

As the critical wave height, provided by equation (25) is 4.9 m, using the data provided by [28] and choosing a strip between 4.5 and 5.5 m, the occurrence probability of this wave is 9.82%. Multiplying the probability of occurrence of the wave by the voyage time, the result is that the ship would be exposed to 35.84 cycles of stress during a year. The ship can sail with the 0.005 m crack for 7 years until it gets to a critical size.

8. CONCLUSION

This paper presents a methodology for the prediction of cracks in ships that may lead to failure. The methodology applies the concepts of Griffith and Paris Law for fracture assessment, considering the strain hardening that is created by the waves cycles contributing to fatigue.

It was hypothesized that only one crack exists in the hull of the ship. Besides, the ship was modelled with the beam theory, disregarding stress concentration in some structures. It was also taken in consideration that just one kind of wave can damage the ship, but in reality every wave will damage the ship cumulatively in fatigue life.

The stress was adjusted by the strain hardening exponent, which was corrected by other factors such as ageing, vibrations and welding. These corrections, at first were estimated as 20%, each one in the strain hardening exponent tested with SAE 1020 sample steel.

To validate the theory and find the value of correction factors, tests with finite element method must be performed and subsequently experimental tests. For future works a local analysis of structural components of the hull aiming to predict the crack growth can be done.

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REFERENCES

[1] Pastoukhov, V. A., Voorwaldm, H. J.: *Introduc–tion to structural integrity mechanics*. São Paulo: UNESP, 1995. (In Portuguese).

[2] Ship Structure Committee: A study of ship hull crack propagation systems, SSC – 265, Washington, 1976.

[3] Fragassa, C., Zivkovic, I., Pavlovic, A.: The accelerated aging effect of salt water on lignocellulosic fibre reinforced composites. Tribology in Industry, Vol. 39, No. 2, 2017.

[4] Zivkovic, I. et al.: Influence of moisture absorption on the impact properties of flax, basalt and hybrid flax/ basalt fiber reinforced green composites. Composites Part B, Vol. 111: pp 148-164, 2017.

[5] Fragassa, C.: From Design to Production: an inte–grated advanced methodology to speed up the indus–trialization of wooden boats. Journal of Ship Pro–duction and Design. Vol. 33, No. 2, pp. 1–10, 2017.

[6] Fotouhi, M. et al.: Effect of PVDF nanofibers on the fracture behavior of composite laminates for high-speed woodworking machines. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science. Vol 231, No. 1, pp. 31-43, 2017

[7] Camargo, F.V. et al.: Cyclic stress analysis of polyester, aramid, polyethylene and liquid crystal polymer yarns. Acta Polytechnica, Vol. 56, No. 5, pp: 402–408, 2016

[8] De Paola, S., Minak, G., Fragassa, C., Pavlovic, A.: Green Composites: A Review of State of Art.

In: 30th Danubla-Adria Symposium on Advances in Experimental Mechanics, DAS 2013 - Proceedings, pp 77-78, 2013.

[9] Hyseni, A., De Paola, S., Minak, G., Fragassa, C.: Mechanical Characterization of EcoComposites. In: 30th Danubla-Adria Symposium on Advances in Experimental Mechanics, DAS 2013 - Proceedings, pp. 175-176, 2013.

[10] Boria, S., Pavlovic, A., Fragassa, C., Santulli, C.: Modeling of Falling Weight Impact Behavior of Hybrid Basalt/Flax Vinylester Composites. Procedia Engineering, Vol. 167, pp 223–230, 2016.

[11] Fragassa, C.: Effect of Natural Fibers and Bio-Resins on Mechanical Properties in Hybrid and Non-Hybrid Composites. AIP Conference Proceedings, Vol. 1736, 2016, doi: 10.1063 /1.4949693

[12] Saghafi, H., et al.: Comparison the effect of pre-stress and curvature of composite laminate under impact loading. FME Transactions: Vol. 44, No. 4: 353-357, 2016.

[13] Petrašinović, D., Rašuo, B., Petrašinović, N.: Extended finite element method (XFEM) applied to aircraft duralumin spar fatigue life estimation. Technical Gazette, Vol. 19(3), pp. 557-562, 2012.

[14] Grbovic, A., Rasuo, B.: "FEM based fatigue crack growth predictions for spar of light aircraft under variable amplitude loading," Eng. Fail. Anal., vol. 26, pp. 50–64, 2012.

[15] Grbovic, M. A., Rašuo, B.: Chapter 2: Use of Modern Numerical Methods for Fatigue Life Predictions (pp.31-74), In: Recent Trends in Fatigue Design, (Ricardo Branco, Editor), Series: Mechanical Engineering Theory and Applications, ISBN: 978-1-61668-410-5, Nova Science Publishers, New York, 2014.

[16] Callister, W. D. *Sciency and materials engineering: an introduction*. LTC, 7 edition. 2008. (In Portuguese).

[17] Inlgis, C. E. Stresses in a plate due to the presence of cracks and sharp corners, in: *Spring meetings od the fifty-fourth session of the Institution of Naval Architects*, p. 55. 1913.

[18] Griffith, A. A. *The phenomena of rupture and flow in solids*. The Royal Society, p. 36. 1921.

[19] Bai, Y. Marine structural design. Kidlington: Elsevier. 2003.

[20] Paris, P. C.et al. A rational analytic theory of fatigue, in: *Trends Engineering*. 1961.

[21] Paris, P. C.; Erdgon, F. Critical analysis of crack propagation laws, in: *Journal of basic engineering*. p. 528-534. 1963.

[22] Al-Qureshi, H. A. Processos e mecanismos da conformação dos metais. Joinville: CEM/UFSC. 2010. (In Portuguese)

[23] Okumoto, Y. et al. Design of ship hull structures – A practical guide for engineers. Japan: Springer. 2009.

[24] Det Norske Veritas – DNV. Hull structural design – Ships with lenght 100 meters and above. Det Norske Veritas. 2015.

[25] Key To Metals. *Strain ageing of steel: part one*. Avaiable in: <http://keytometals.com/page.aspx?ID=CheckArtcle&site=kts&LN=PT&NM=392>. Access in: 24.mar.2015.

[26] R. Branco, Recent Trends in Fatigue Desing. New York: Nova Science Publishers, 2015.

[27] The Royal Institution of Naval Architects. Significant Ships of 2010. LondON: The Royal Institution of Naval Architects. 2011.

[28] Amerian Bureau of Shipping – ABS. Guide for spectral based fatigue analysis for floating production, storage and offloading (FPSO) installations. Houston, 2010.

NOMENCLATURE

a	half of the crack's length
U	potential energy of the plate with the crack
U_0	potential energy of the plate without the crack
E	Young's modulus
K_C	critical stress intensity factor
K_{IC}	critical stress intensity factor for mode I
Y	constant regarding the place of the crack in the plate
ΔK	Stress intensity factor variation
$\partial a/\partial N$	crack growth rate,
C	material constant
m	material constant,
N_f	number of cycles until failure
a_c	critical length of the crack
a_i	initial length of the crack
A	material constant
n	strain hardening parameter
L	length of the ship
B	beam of the ship
D	the depth of the ship
C_B	block coefficient
∇	volume of the hull
T	draught of the ship
M_{ST}	bending moment in calm sea for sagging condition
M_{SA}	bending moments in calm sea for hogging condition
C_W	wave coefficient
M_{WT}	bending moment in seas with waves for sagging condition
I	inertial moment of area
Z	section modulus
f_1	constant depending on the yielding stress
H	critical wave height
n^*	new hardening exponent coefficient
K_E	ageing coefficient
K_V	vibration coefficient
K_S	Welding coefficient

GREEK SYMBOLS

σ_{max}	maximum stress that can be applied in the material
σ_c	material-dependent critical stress

P	radius of the crack edge
Σ	stress
γ_S	superficial energy of the material
$\bar{\sigma}$	real stress
$\bar{\varepsilon}$	real strain
α	coefficient related to navigation conditions
σ_Y	yielding stress of the material

МЕТОДОЛОГИЈА ЗА ПРЕДВИДЈАЊЕ ПРОПАГАЦИЈЕ ПУКОТИНЕ ПРИМЕЊЕНА НА СЛУЧАЈУ КАРГО НОСАЧА

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Овај рад представља методологију оцјењивање са циљемпредвиђања ширења пукотина у бродовима у случају дуктилног материјала под заморним оптерећењем. Ова методологија, заснована на линеарној еластичној механици лома, резултат је прегледа литературе из механике континуума који се примењује у области бродоградње. Добијен математички редослед се заснива на теорији енергије која је повезана са већ постојећим ломом примењеним Paris законом који се односи на брзину простирања величине лома, варијације напона и броја циклуса све док не достигне критичну величину. Примена корекције фактора напона узет је у обзир због очвршћавања које доводи до пластичности у региону пукотине. Да би се доказала примена предложене методологе у области бродоградње коришћен је модел карго носача. Развој овог рада треба да допринесе са математичког модела који омогућава да се предвиди ширење лома под утицајем замора.