

Methodology for Crack Growth Analysis in Ship Hull Structures Using Sea Wave Forecasting Models

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Abstract

Naval structures, such as ships and other artifacts, have a limited-service lifespan and begin to degrade as soon as they enter service due to fatigue and fracturing processes. To manage this deterioration, periodic inspections are needed to determine corrective actions on cracked structures. Structural Health Monitoring (SHM) systems are designed to continuously measure or periodically monitor cracked components, helping to prevent catastrophic failures. This paper presents a methodology to assess the integrity and remaining service lifespan of cracked structural components on ships through a combination of numerical computation, SHM system data on crack size, combined with satellite-based meteo-marine data. This methodology seeks to plan maintenance or repair operations in shipyards. Marine loads on the ship's route are obtained using geolocation tools and satellite meteo-marine information systems. Using NOAA's WaveWatch III for wave prediction and seakeeping analysis based on future wave spectra, the future likely behavior of the ship is determined. The hydrodynamic loads and accelerations are transferred to a mechanical structural model based on the Finite Element Method to evaluate the structural response of the affected component. The state of stress and strain in the crack zone is determined by sub-modeling. The Extended Finite Element Method (XFEM) is used to analyze the crack fatigue and estimate its remaining service life, based on fracture growth models.

Key words: Naval structures, fracture, Structural Health Monitoring, Seakeeping, Extended Finite Element Method, Fatigue fracture growth, WaveWatch model, Crack Growth, Ship hull structures.

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Introduction

By deploying sensor networks and advanced data analytics, SHM enables continuous surveillance of structural integrity, facilitating early detection of defects or degradation without necessitating system downtime. This paradigm shift from conventional testing and inspection methodologies towards real-time monitoring aligns with the imperative of ensuring the safety and longevity of critical infrastructure, including maritime assets such as ships and naval structures. The development of an advanced SHM system tailored for maritime applications represents a significant stride towards proactive maintenance strategies in the maritime domain. Recent studies reveal significant progress in this domain, addressing complex challenges and enhancing the accuracy of structural predictions and safety assessments. Notably, [1] tackles the integration of seakeeping loads into structural finite-element models, introducing a quadratic programming method to improve model equilibrium and accuracy. Similarly, [2] offers a hybrid approach that combines strip theory with finite element methods to enhance the efficiency of seakeeping load transfers in ship design. An innovative method that merges experimental vibration tests with the Pseudo Simplified model technique is presented in [3], enabling effective damage detection despite limited modal data.

Meanwhile, [4] explores plasticity-induced crack closure and its application to time-dependent loading sequences, refining fatigue fracture predictions for ship structures. Dynamic behaviour of structural cracked plates and shallow shells using the Boundary Element Method was explored in [5] and [6]. The behavior of ships under dynamic and hydroelastic loads has also seen substantial development; [7] introduces a 3D nonlinear time-domain hydroelastic analysis method for asymmetric slamming effects, while [8] develops a comprehensive hydroelastic theory that accounts for nonlinear hydrostatic

restoring forces and evaluates the dynamic response of flexible hulls. Additionally, [9] critically assesses constitutive models for shipbuilding materials, evaluating their performance across various failure criteria.

Furthermore, the integration of SHM into the maritime industry heralds transformative implications beyond mere maintenance routines. By fostering a culture of predictive maintenance and risk mitigation, SHM catalyzes a paradigm shift towards data-driven decision-making and asset management strategies. This holistic approach not only enhances operational efficiency and safety but also engenders cost savings by minimizing unplanned downtime and maximizing asset utilization. Moreover, the wealth of real-time data generated by SHM systems holds immense potential for informing design optimizations and regulatory compliance, thereby fostering innovation and sustainability across the maritime sector. The project in question aims primarily at developing an advanced Structural Health Monitoring methodology to follow up on the structural behavior of ships, with a primary focus on the surveillance and tracking of specific anomalies such as cracks, under specific wave conditions imposed on the ship according to the navigation route. In the following sections, the methodological framework, results, and conclusions are presented, as well as the conclusions of the methodology obtained.

Framework

Navigation Path Coordinate Estimation

To know the navigation route of the ship of interest, as well as the coordinates of the path it follows, it is necessary to access wave forecast data, as is calculated and varies along the ship's route. The navigation route of ships in real time can be accessed by marine analytics providers as Marine Traffic [10] to calculate the coordinates of a trajectory. Using the Haversine formula to calculate the

distance between the start and end point of the trajectory:

$$a = \sin^2\left(\frac{\Delta\varnothing}{2}\right) + \cos(\varnothing_1) \cdot \cos(\varnothing_2) \cdot \sin^2\left(\frac{\Delta\lambda}{2}\right) \quad (1)$$

$$c = 2 * \arctan(\sqrt{a}, \sqrt{1-a}) \quad (2)$$

$$d = R * c \quad (3)$$

Where:

a is an intermediate measurement used to calculate the central angle. The value of a is in the range [0,1]. When $a=0$, it means that the two points are identical or along the same line of latitude or longitude. When $a=1$, it means that the points are at opposite ends of the sphere.

c is the central angle in radians between the two points on the surface of the sphere. The value of c is in the range [0, π]. When $c=0$, the two points are identical. When $c=\pi$, the points are at opposite ends of the sphere.

d is the distance "in a straight line" on the surface of the sphere between the two points.

\varnothing_1 and \varnothing_2 are the latitudes of the two points in radians.

$\Delta\varnothing$ is the difference between the latitudes of the two points: $\Delta\varnothing = \varnothing_2 - \varnothing_1$

$\Delta\lambda$ is the difference between the lengths of the two points: $\Delta\lambda = \lambda_2 - \lambda_1$

R is the radius of the sphere (e.g., the average radius of the Earth, which is approximately 6,371km).

Sea Wave Forecast

WAVEWATCH III, developed by National Oceanic and Atmospheric Administration (NOAA), is a third-generation wave model developed to simulate and predict ocean wave conditions [11]. It integrates various physical processes, equations, and numerical methods to provide accurate wave forecasts. WAVEWATCH III model forecasts output data [12], which includes parameters such as wave height, wave

direction, and wave frequency, and can be accessed through services such as THREDDS (Thematic Real-time Environmental Distributed Data Services), managed by Unidata. Unidata is an organization that provides resources for the management, distribution, and visualization of atmospheric, oceanographic, and climate data, and can provide access to data generated by the WAVEWATCH III model [13]. The THREDDS Data Server has datasets corresponding to WW3 climate prediction models. The data format used is GRIB2, which is a file format for storing and transporting gridded meteorological data, such as that resulting from numerical weather prediction models. A GRIB2 file contains one or more data records, arranged as a sequential stream of bits. Each record begins with a header, followed by packed binary data. The header consists of 8-bit unsigned numbers (octets) [14].

The TDS website shows a catalog with all the Data Sets it hosts (the link to the server can be found in the references). WW3 is located in the Forecast Model Data section, where the real-time information of the forecast model can be found. After accessing Wave Watch III Global, all the grib2 documents contain the sea state information by date, where you will obtain the period, direction and wave height information for the current date when accessing the server and a time coverage of 7.5 days. The wave model has a spatial resolution of 0.25 x 0.25 degrees. The system runs four cycles per day (00Z, 06Z, 12Z and 18Z) [15].

The server allows us to know all the characteristics of the grib2 document, where it is specified that the spatial resolution of the model for Longitude is from 0.0 to 359.5 with a Resolution=0.5 degrees west and for Latitude from -77.5 to 90.0 with a Resolution=0.5 degrees north. For this project, we will use the NCSS (NetCDF Subset Service), a THREDDS Data Server tool that facilitates the query and extraction of specific subsets of data, providing an efficient interface for browsing, viewing and downloading data from the WAVEWATCH III model.

Sea Wave State along navigation path

Once the trajectory has been calculated, a Python code developed by the authors downloads weather data from the server by using an API based on the NCSS (NetCDF Subset Service) protocol. Functions are used to generate dates and build the necessary queries for data retrieval. The downloaded data is stored in CSV files that are combined into a pandas DataFrame for easy analysis. The DataFrame is cleaned and renamed as needed to ensure that the columns are easily understandable. The code requires route coordinates and start time/date as input. It extracts Direction, Period, and Height for each coordinate along the route, generating an output dataset that will be entered as input parameters for hydrodynamic analysis performed in engineering software such as ANSYS AQWA.

Seakeeping Analysis

The Seakeeping analysis is essential for evaluating a vessel's movements and hydrodynamic forces under anticipated sea states. Specialized computational tools, such as ANSYS AQWA, are employed for this purpose, where Hydrodynamic Diffraction and Hydrodynamic Response analysis were handled. It is noteworthy that only the external surface of the ship is considered in hydrodynamic assessments. ANSYS AQWA employs the Hess-Smith panel method to solve fluid dynamics problems [16]. The velocity potential in the flow field around a floating body is defined by equation (4).

$$\varphi(\vec{X})e^{-i\omega t} = \left[(\varphi_i + \varphi_d) + \sum_{j=1}^6 \varphi_{r,j} \chi_j \right] e^{-i\omega t} \quad (4)$$

Where φ_i is the incident wave potential, φ_d is the corresponding diffraction wave potential, $\varphi_{r,j}$ is the radiation wave potential. When the wave velocity potentials are known, the first order hydrodynamic pressure distribution can

be calculated using the linearized Bernoulli equation (5) [16].

$$P = -\rho \partial \varphi(X, t) / \partial t = i\omega \rho \varphi(X) e^{-i\omega t} \quad (5)$$

From the pressure distribution, the various fluid forces can be calculated by integrating the pressure on the wetted surface of the body (6).

$$F_j e^{-i\omega t} = - \int_S P \cdot n_j dS = - \left[i\omega \rho \int_S \varphi(\vec{X}) \cdot n_j dS \right] e^{-i\omega t} \quad (6)$$

Similarly, the panel method is utilized to discretize the ship surface, thus facilitating a detailed analysis of how sea pressures influence the vessel. The body surface is divided in N panels small enough to assume that the strength of the sources and doublets and the fluid pressure is constant over each element [17].

Factors such as water depth, wave frequencies, and direction are integrated into the model to accurately simulate real conditions encountered along the ship's intended route. The panel method is usually restricted to arbitrarily shaped bodies with zero mean forward speed. This is an acceptable simplification for the majority of the fixed or floating structures in use today in the offshore industry. This numerical method calculates the (potential) flow around a body, based on the principle of Green's integral theorem (7).

$$\varphi_t(P) = U_a(P) + \sum_i^{=1n} \left(1/|r_p - r_Q| \right) \sigma(Q) ds_i \quad (7)$$

Where $\sigma(Q)$ is the charge density on the panel, r_p and r_Q are the vectors of points P and Q, and ds_i is the differential element of length over the panel. According to this theorem, it is possible to transform a three-dimensional linear homogeneous differential equation into a two-dimensional integral equation. In that way, the three-dimensional Laplace (potential) equation can be transformed

into a surface integral equation, known as Green's identity:

$$\nabla^2\phi = \nabla^2G(P, Q) = 0 \quad (8)$$

The integral equation represents a distribution of sources (or sinks) and dipoles on the surface. To solve the integral equation numerically, the surface of the body is discretized into panels. The body surface is divided into N panels (which will compose the mesh of the model) small enough to assume that the strength of the sources and doublets and the fluid pressure is constant over each element. The granularity of the mesh dictates the frequencies accommodated by the model, ensuring a comprehensive understanding of the vessel's response to sea dynamics. Now a set of integral equations is made, from which the velocity potentials can be found.

$$\phi_t(P) = \phi_{ex,t}(P) + \sum_i^{=1n} \int G(P, Q) \sigma(Q) ds_i \quad (9)$$

The integral equation can be discretized for each panel by substituting an unknown strength of the source and the dipole distribution. By using the boundary condition of tangential flow, the unknown strength of the sources and dipoles can be solved [17]. Panel methods are the most common technique used to analyze the linear steady state response of large-volume structures in regular waves. A wave spectrum is used to describe a sea state and irregular sea results can be obtained by linear superposition of results from regular incident waves, which direction, amplitude, frequency and period characterization were obtained from the SeaWave prediction model applied into the expected zone of navigation as described in section 2.3 and used as input for the Hydrodynamic Response Time Domain Analysis.

Finite Element Ship-Hull Structure Analysis

In the quantification of the global and local loads acting on a vessel, waves play a crucial

role in analyzing their behavior. There are both traditional and advanced methods [18] that enable the quantification of inertial loads related to external pressures, vessel motions, and accelerations. This provides relevant information for assessing other types of loads, such as slamming and rolling. The traditional analysis is based on a quasi-static approach where the vessel is statically positioned in a wave with specific characteristics, and it is balanced between weight and buoyancy. This procedure is based on the trochoidal wave profile derived from static wave research and is used to calculate hydrostatic pressures on the hull surface. In the finite element model, the correct placement of the wave profile is crucial to establish equilibrium. In accordance with established practices documented in the literature [19]; boundary conditions for the model are defined at the ship's extremities to restrain rigid-body motions in the responses obtained through the finite element method. Various loads, including self-weight, interaction forces between the structure and waves, and hydrostatic pressure, are incorporated into the model.

To obtain more accurate results, a submodel was developed to analyze the special structural elements of the ship with greater precision. The transfer of the load from the global model to the submodel was accomplished by using the nodal displacements calculated in the global model and applying them as boundary conditions for the submodel, in accordance with the procedures described in [20] [21]. The load spectrum was calculated according to section 2.4. Linear plate elements were used in the overall model, while linear brick elements were employed for the submodel. The submodels utilized a structurally refined mesh with an aspect ratio of 1:1 and at least three elements in thickness, ensuring detailed stress distribution analysis. Structural elements were chosen for the submodels where defects, such as cracks, are more common [22].

Through-thickness cracks were simulated in the submodel, with elements in the vicinity of

the crack refined to have a length of at least 1/20 of the minimum crack length. Additionally, a refinement spider-web mesh at the crack tip was implemented to achieve more accurate stress intensity factor calculations and better overall results, as recommended in the literature on Engineering Fracture Mechanics [22] [23] [24]. The precise mesh refinement is crucial for capturing the intricate details of crack propagation and its impact on structural integrity.

Extended Finite Element Method

The defect analyzed in the local model is a crack, which is significantly smaller in scale compared to the entire structure and even the defined submodel. To accurately describe the structural behavior of this crack, the Extended Finite Element Method (XFEM) will be employed. The approximation function for displacement will be defined as follows [10]:

$$u(x) = \sum_{i \in N_n(x)} a_i \phi_i(x) + \sum_{j \in N_n(x) \cap K} b_j \phi_j(x) H(D(x)) + \sum_{k \in N_n(x) \cap L} \sum_{\alpha=1}^4 c_k^\alpha \phi_k(x) F^\alpha(D(x)) \quad (10)$$

The first term of Eq. (10) pertains to the classical FEM formulation, where a_i represents the displacement degrees of freedom at node i , $\phi_i(x)$ denotes the shape function and $N_n(x)$ includes all nodes that influence the node with coordinates x .

The second term in Eq. (10) corresponds to the enrichment function integrated into the XFEM formulation. This term addresses the discontinuity introduced by the crack, where k encompasses the nodes whose support domain is fully intersected by the crack. The function $D(x)$ quantifies the distance between the crack and the node x , b_j represents the degrees of freedom of the enriched nodes, and $H(x)$ is the Heaviside function defined at x , determined by Eq (11). The positive or

negative sign of the Heaviside function will establish whether the node is located above or below the crack.

$$H(x) = \begin{cases} -1 & \text{if } x < 0 \\ +1 & \text{if } x \geq 0 \end{cases} \quad (11)$$

The third term in Eq. (10) pertains to the enrichment applied to nodes whose support domains are partially intersected by the crack, specifically the nodes located at the crack tips. To accurately capture the singularities at these nodes, enrichment is performed using the asymptotic functions proposed by Williams [11]:

$$F = \left[\sqrt{r} \sin \frac{\theta}{2}, \sqrt{r} \cos \frac{\theta}{2}, \sqrt{r} \sin \frac{\theta}{2} \sin \theta, \sqrt{r} \cos \frac{\theta}{2} \sin \theta \right] \quad (12)$$

The polar coordinates of the nodes relative to the crack tips are denoted by (r, θ) , where L represents the set of nodes at the crack tips. c_k^α represents the degrees of freedom associated with the k -th node at the crack tip regarding the singularity function α .

Crack Grow Model

The purely geometrical approach of crack propagation was employed as a model for predicting how cracks spread. It utilizes a vectorial approach from the crack tip, considering its local coordinate system to estimate distances and forecast crack growth [12]. This method focuses on analyzing how cracks disseminate based on their position and orientation relative to the material's structure and loading conditions. This approach provided a robust framework for assessing the durability and service lifespan of the ship under varying loading conditions, thus contributing to enhanced safety and performance predictions. In this method, the crack propagation velocity field is calculated by using Eq. (7) [12].

$$V = C_p G^m (\sin(\beta) e_1 + \cos(\beta) e_2) \quad (13)$$

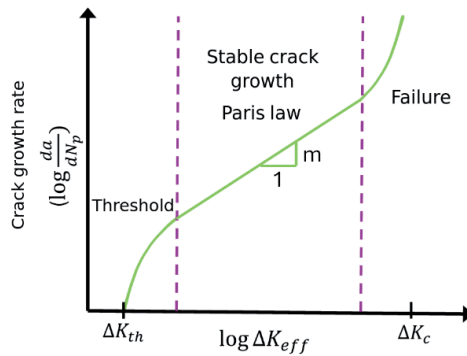
The parameters c_p and m are material constants derived from Paris' law, while e_1 and e_2 are unit vectors in the local coordinate system. The crack propagation direction angle β is defined by the expression.

$$\beta = 2 \arctan \left(\frac{1}{4} \left(\frac{K_I}{K_{II}} - \text{sign}(K_{II}) \sqrt{\frac{K_I^2}{(K_{II})^2} + 8} \right) \right) \quad (14)$$

Damage model

Paris' law was employed for the damage model, which delineates crack propagation into three distinct phases: an initial phase where no crack growth is observed, a subsequent phase characterized by controlled crack growth, and a final phase where the potential for failure becomes significant, as seen in Fig. 1. The crack growth according to Paris' law is defined by Eq. (9).

Fig. 1. Crack growth Rate versus Stress intensity factor range according to Paris' Law.



$$\frac{da}{dN} = C (\Delta K_{eff})^m \quad (15)$$

ΔK represents the difference between the stress intensity factors at the upper and lower stress limits during cyclic loading. da/dN are the crack growth rate, and C and m are the material constants obtained for [13].

The direction of crack propagation was calculated based on the maximum principal

stress at the crack tip, as proposed by Erdogan and Sih [14]. It was postulated that the crack would grow in a direction perpendicular to the maximum principal stress. The local crack-extension direction (θ) was then calculated by ensuring that the crack-tip shear stress is zero, as given by the following equation:

$$K_I \sin(\theta) + K_{II} (3 \cos(\theta) - 1) = 0 \quad (16)$$

Where the stress intensity factors K_I and K_{II} will be calculated according to the G-theta method as defined in [15]. This method is based on computing the J-integral matrix by considering the energy release rate with a bilinear symmetric form and employs the formulas proposed by Irwin [15].

Considering that loading conditions will be derived from a transcendent model, which will subsequently be recalculated at various points along the vessel's trajectory, and that all these variants will record different loading conditions, a weighted summation of the remaining fatigue life cycles for these conditions must be performed, as illustrated in the following equation:

$$N_{final} = \frac{\sum_{i=1}^n N_p^i}{\sum_{i=1}^n N_{real}^i} \quad (17)$$

Where N_{real}^i represents the number of cycles during which the load is repeated within the evaluated trajectory, N_p^i denotes the number of cycles the vessel can endure under the load i before reaching the target crack length, and N_{final} indicates the number of trajectories the vessel could endure before achieving the target crack length.

Results

The proposed SHM model is an integrated system in which data is processed across different software tools following a direct workflow. Wave loads obtained from a sea-wave prediction model are used as input in fluid-structure interaction models for the

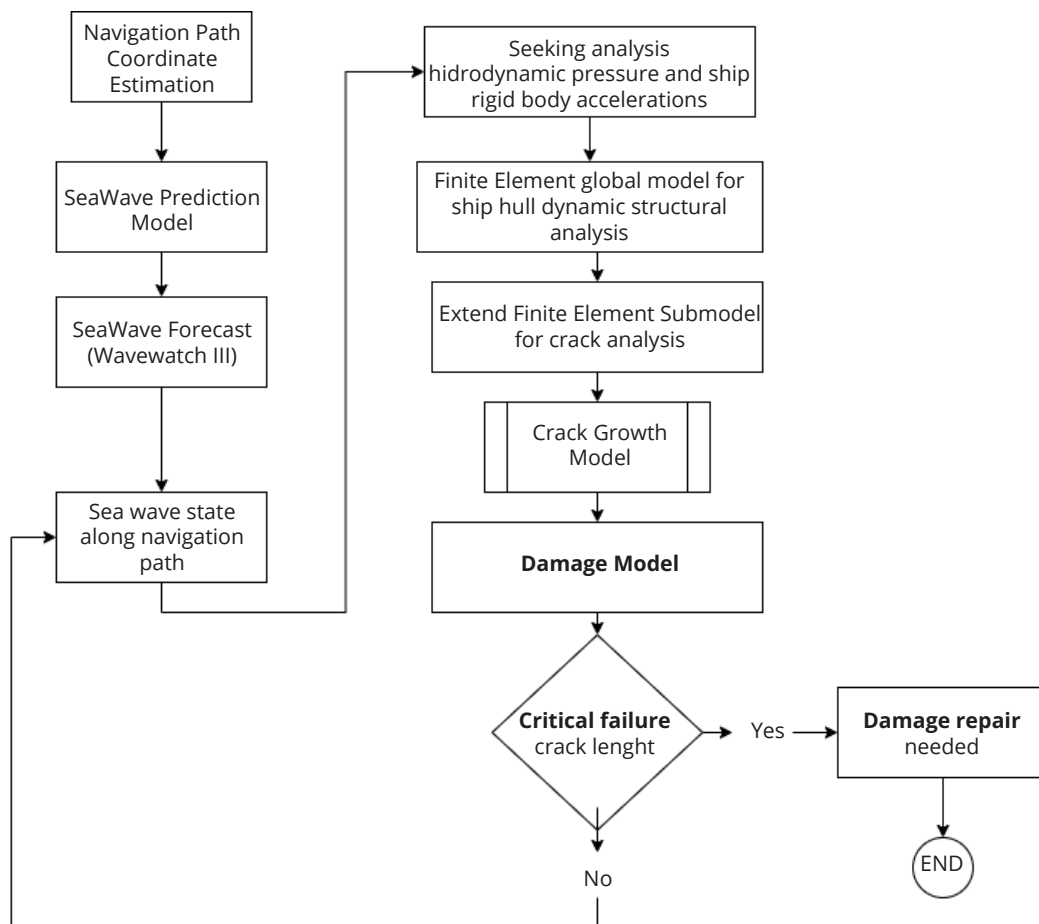
seakeeping analysis of the vessel, from which dynamic structural loads are derived. These dynamic loads are subsequently employed in a computational fracture mechanics-based crack growth model for fatigue life prediction using the Finite Element Method. This information is essential for understanding the vessel's future behavior under different sea conditions. A general flowchart of the proposed methodology is shown in Fig. 2.

The system considers meteorological conditions, especially wave loads, which can affect the structural health of the vessel during its navigation route. It uses satellite data and models predicting sea conditions to determine wave height and frequency along the planned route. The Sea Keeping analysis is employed to assess the ship's movements and hydrodynamic loads based on forecasted

sea conditions. Specialized numerical simulation software such as ANSYS Aqwa [16] is used for this analysis. Once the sea loads are determined, a finite element model of the ship's structure is constructed, focusing on the region where the crack is located. This model allows for the determination of stresses and deformations along the ship's hull. With the information provided by the data acquisition system regarding the crack's size, dimensions, and geometry at any given time, a detailed analysis of crack growth due to fatigue is carried out.

Future work could involve incorporating a real-time monitoring system with sensors installed around potential crack growth zones on navigating ships. Classification Societies, such as the American Bureau of Shipping and Bureau Veritas, have their own

Fig. 2. Flowchart proposed for SHM methodology.



guidelines for applying crack monitoring and structural health monitoring in general in vessels, with methodologies leaning more towards condition monitoring systems [31]. A comprehensive structural health monitoring plan for fatigue cracks in structures should encompass sensors, data acquisition, data utilization, data processing, analysis, and analytics models [32]. Hull monitoring systems are designed to acquire, display, and/or record information and then utilize that information for decision-making to enhance operational efficiency and safety [33].

Conclusions

The comprehensive analysis of structural integrity and performance characteristics of maritime vessels through advanced computational techniques is crucial for ensuring their safety and longevity. By utilizing methods such as finite element analysis (FEA), dynamic load assessments can be effectively predicted, offering valuable insights into the vessel's structural behavior under various conditions. These analyses contribute significantly to maintaining compliance with regulatory standards and industry best practices, ensuring both the safety and operational efficiency of maritime operations.

A key outcome of this study is the proposed methodology for analyzing crack-type defects in a vessel's hull. This methodology can be used to assess whether the vessel can continue its planned route or requires immediate repairs. By integrating real-time oceanographic data from online databases, along with defect monitoring systems, the methodology provides dynamic predictions of load conditions throughout the vessel. Specifically, it enables an understanding of the unique load conditions acting on the defect itself.

In this methodology, several advanced techniques are combined: satellite-based prevention systems, boundary element

methods (to simulate vessel-water interaction), finite element methods (to simulate the vessel's structural response), extended finite element methods (to model defect load conditions), crack propagation models (to predict crack behavior along the vessel's route), and failure analysis methods (to evaluate the vessel's fitness for service and the extent of damage). Altogether, these methods form a robust framework for ensuring safe vessel operation, even in the presence of structural defects.

The implementation of such an integrated methodology will not only aid in real-time decision-making regarding vessel maintenance but will also provide a proactive approach to preventing catastrophic failures. Moving forward, the validation of this methodology through realistic case studies will be essential to demonstrate its practical advantages and to systematize the entire process for broader application across the maritime industry. This continuous refinement will ultimately enhance the safety, efficiency, and sustainability of maritime operations, ensuring safer voyages despite potential structural defects.

Contributions

- Jairo Useche: Conceptualization, methodology, formal analysis, writing review and editing, visualization, supervision, project administration, funding acquisition.
- Kevin Patron : Methodology, validation, resources, visualization, supervision.
- Raquel Rey : Software, formal analysis, investigation, data curation, writing original draft preparation
- Miguel Rodelo : Software, formal analysis, investigation, data curation,
- Jose Martinez : Software, formal analysis, investigation, data curation, writing original draft preparation, supervision

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