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Real-time risk of ship structures integrating structural health monitoring data: Application to multi-objective optimal ship routing

Alberto Decò, Dan M. Frangopol *

Department of Civil & Environmental Engineering, Engineering Research Center for Advanced Technology for Large Structural Systems (ATLSS), Lehigh University, Bethlehem, PA 18015-4729, USA

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A B S T R A C T

The aim of this paper is to develop a risk-informed approach for ship structures that integrates structural health monitoring (SHM) information. As an application, real-time optimal short range routing of ships is presented. Risk is based on the reliability analysis of the midship section of a hull and on its associated failure consequences. Different damage levels, accounting for the propagation of plastification throughout the hull section, are considered. Ship age is also investigated by including the effects of corrosion. SHM data, integrated within the developed decision support tool, provides useful information to be used during the real-time decision process. A novel closed-form solution for short term statistics based on Rayleigh prior distribution and a simulation-based technique are proposed for Bayesian updating. Finally, optimal short range routing of ships is accomplished by solving two- and three-objective optimization problems, in which the objectives to be minimized are the estimated time of arrival, mean total risk, and fuel cost, given sea weather maps and origin and destination points. Weather forecast, associated with different time frames, is also included within the developed framework. The solutions are obtained in the form of Pareto-optimal sets. The proposed approach is illustrated on a Joint High-Speed Sealift.

1. Introduction

Obtaining accurate information regarding ship structural safety is fundamental for the optimal planning of ship routes. Generally, decision makers are mainly required to reduce fuel cost, maximize ship safety, and minimize the mission/delivery time. Special effort is needed for the development of approaches accounting for reliability and risk, as measures of the structural performance, and for operational cost, predicted to increase in the long-term due to gas price (now fluctuating). In this context, besides the initial planned route and initial ship structural performance assessment, the availability of further information during the ship trip becomes a key aspect to consider. For instance, information from structural health monitoring (SHM) systems can improve the evaluation of the structural performance while the ship is traveling. Besides, the continuous weather prediction would make the adjustment of the planned route possible. This further collected information brings route planning close to a real-time decision process, necessary in order to better achieve all the above mentioned objectives.

Ship structural safety may be evaluated by considering mere reliability analysis that does not account for consequences. However, the inclusion of the induced economic losses due to potential structural failures or malfunctions plays a central role in the decision analysis leading to risk assessment (IMO, 1997; Akpan et al., 2002; Ayyub et al., 2002; Skjong, 2002; Skjong and Bitner-Gregersen, 2002; IMO, 2006; Decò and Frangopol, 2013; Dong and Frangopol, 2015). In this paper, risk is evaluated with respect to the flexural failure mode of ship hulls, which is considered one of the most critical aspects (Paik et al., 1998; Guedes Soares and Teixeira, 2000; Lua and Hess, 2003; Okasha and Frangopol, 2010; Okasha et al., 2010; Decò et al., 2011; Decò et al., 2012; Frangopol et al., 2012). Several limit states accounting for the progressive collapse mechanisms of plates and stiffeners are investigated in order to quantify the proper amount of economic losses (Decò and Frangopol, 2013). Accordingly, reliability analysis is performed with respect to intermediate states associated with different plastification propagation levels within the hull girder, accounting for both vertical and horizontal flexures. A finite element (FE) model of a Joint High-Speed Sealift (JHSS) (Devine, 2009), built using the software ABAQUS (Dassault Systèmes Simulia, 2011), has been used, and non-linear analysis has been performed in this paper. The relevant uncertainties affecting the load and strength predictions are accounted for,

* Corresponding author. Tel.: +1 610 758 6103; fax: +1 610 758 4115.
E-mail address: dan.frangopol@lehigh.edu (D.M. Frangopol).

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including random variables associated with material and geometric properties.

The main scope of this paper is the development of an approach for the real-time assessment of risk that integrates the initial risk prediction with data obtained from SHM and provides decision makers with a set of optimal route alternatives in order to meet risk and reliability targets. Bayesian statistics has been used for this purpose. Both a proposed closed-form solution and a simulation-based technique are used in this paper based on the assumption that the peak responses follow the Rayleigh distribution (Faltinsen, 1990). SHM is considered a very powerful tool to be used for the collection of accurate information about the responses due to the actual loads that ships encounter during their operations. The SHM data used in this paper are obtained from a scaled model of the JHSS tested in the summer of 2007 in the Naval Surface Warfare Center, Carderock Division – Maneuvering and Sea Keeping (NSWC CD – MASK) basin. The observations in terms of vertical and horizontal bending moments (VBM and HBM, respectively) are then scaled up to the ship full dimensions by using the Froude-scaling factor of 47.2533 (Devine, 2009). Lastly, an application on optimal short range routing of ships is developed considering risk as the main performance indicator. Ship routing is an important and interesting part of ship management (Journée and Meijers, 1980; Spaans, 1985; Brown et al., 1987; Hagiwara, 1989; Bijlsma, 2008; Szłapczynska and Smierzchalski, 2009; Hinnenthal, 2008; Dolinskaya et al., 2009; Bijlsma, 2010; Fagerholt et al., 2010; Tsou, 2010; Papatzanakis et al., 2012; Chang et al., 2013; Decò and Frangopol, 2013). SHM and weather prediction are considered within the proposed optimization framework, with objectives being the minimization of the estimated time of arrival (ETA), minimization of mean total risk, and minimization of the fuel cost. The cases, in which the use of the original and updated (by using SHM data) performance prediction are considered, are investigated in order to provide insights on the importance of accounting for SHM. The optimal solutions are grouped into Pareto-optimal sets that show the conflicting objectives. The approach is illustrated on the JHSS.

2. Reliability, cost, and risk

Ships are subjected to numerous types of hazard that may directly or indirectly affect their safety and serviceability. For instance, these hazards could be (Ayyub et al., 2002; Skjong and Bitner-Gregersen, 2002) fire, explosion, environmental attack, collision, iceberg impact, grounding, loss of hull integrity, propulsion and steering failures, extreme wave loads, flooding, and capsizing. In this paper, ship vulnerability is assessed with respect to wave-induced loads, which generate vertical and horizontal bending moments (VBM and HBM, respectively) on the ship hull (Paik et al., 1996; Gordo and Guedes Soares, 1997). Sagging and hogging VBMs are categorized depending upon the location of the induced compression that could occur within the deck or the keel, respectively.

Although risk may be evaluated based only on yielding and ultimate limit states, it is worth investigating different effects on the ship hull by considering multiple and progressive levels of danger (Decò and Frangopol, 2013), in order to evaluate costs/risk with a better accuracy. Accordingly, the hull strength is discretized into five states ($S1$ to $S5$), accounting for different levels of section plastification characterized by four limit states LSi as follows:

- Limit state $LS1$: some stiffened plates at the hull extremities reach the yielding stress, therefore they are likely to plastify.
- Limit state $LS2$: the plastification propagates to nearby components up to 20% of the largest distance between the neutral axis and the extreme plates that may experience local buckling.
- Limit state $LS3$: the plastification propagates through the hull section, reaching 50% of the largest distance to the neutral.
- Limit state $LS4$: the plastification propagates throughout the whole section, and the hull ultimate flexural capacity is reached.

In this paper, the FE method is integrated with response surface analysis in order to attain feasible computational time while still being able to account for uncertainties (Bucher and Bourgund, 1990). Material and geometric non-linearities are considered, and incremental method is used to perform FE analysis. According to Gordo and Guedes Soares (1997), the interaction domains associated with the plastification propagation, accounting for the combined effects of VBM and HBM, are obtained by FE simulations. The effects of corrosion, which is a time-dependent process, are included in the methodology according to the approach proposed by (Akpan et al., 2002). A detailed explanation of the methodology can be found in Decò and Frangopol (2013).

For the evaluation of the load effects associated with stillwater VBM, the approach proposed by Hussein and Guedes Soares (2009) is used. Accordingly, the statistical descriptors of the VBMs for sagging and hogging are based on the values provided by IACS (2008). For the evaluation of the wave-induced VBM and HBM, short term statistics are considered. Based on linear theory, the hull responses induced by waves are evaluated by the strip method (Korvin-Kroukowski and Jacobs, 1957). This approach is common practice (Ayyub et al., 2000), however other approaches can be accommodated in the proposed framework, such as non-linear methods. According to Hughes (1983), the probability density function (PDF) of the peak responses associated with different operational conditions follows the Rayleigh distribution

$$f(M_{w,Hs,U,H}) = \frac{M_{w,Hs,U,H}}{m_{0,Hs,U,H}} e^{-\left((M_{w,Hs,U,H})^2/2m_{0,Hs,U,H}\right)} \qquad m_{0,Hs,U,H}, M_{w,Hs,U,H} \geq 0 \tag{1}$$

where the subscripts Hs, U, and H are the significant wave height, ship speed, and heading, respectively, $M_{w,Hs,U,H}$ is the wave-induced VBM or HBM, and $m_{0,Hs,U,H}$ is the zero-th moment of the response spectrum. Moreover, the further contribution due to the dynamic bending moment M_{WH} is evaluated according to Sikora and Brady (1989).

Once the hull strength and the acting load effects are calculated, the probability of a ship hull exceeding the limit states LSi are evaluated based on a time-dependent performance function $G_{LSi,SE,U,H}(t)$ that accounts for damage/failure domains. Therefore, the flexural failure mode given specific ship operational conditions is governed by (Guedes Soares and Teixeira, 2000; Paik and Frieze, 2001)

$$G_{LSi,Hs,U,H}(t) = \delta - \left(\frac{x_w M_{wh,Hs,U,H}}{x_R M_{h,LSi}(t)}\right)^{c_{2,LSi}} - \left(\frac{x_{sw} M_{sw} + x_w k_W (M_{wv,Hs,U,H} + k_D M_{WH})}{x_R M_{v,LSi}(t)}\right)^{c_{1,LSi}} = 0 \tag{2}$$

where x_w, x_R, and x_{sw} are parameters related to model uncertainties referring to the prediction of wave-induced bending moment, resistance, and still water bending moment, respectively, M_{sw}, M_{WH}, $M_{wh,Hs,U,H}$, and $M_{wv,Hs,U,H}$ are the still water VBM, whipping VBM, and wave-induced bending moments (HBM and VBM), respectively, $M_{v,LSi}(t)$ and $M_{h,LSi}(t)$ are the time-dependent vertical and horizontal flexural strengths associated with limit state LSi, respectively, k_W is the correlation factor of the wave-induced bending moment (equal to one according to Mansour et al., 1984), k_D is the correlation factor between wave-induced and dynamic bending moments (Mansour et al., 1984), and $c_{1,LSi}$, $c_{2,LSi}$, and δ are the interaction domain parameters.

There are many types of costs/losses that are involved in ship management. Two types of costs are considered herein, i.e. monetary consequences in terms of losses and operational costs. Both types of costs are included in the proposed approach for ship optimal routing.