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Fatigue damage variation within a class of naval ships

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ABSTRACT

Fatigue damage variation due to operating area differences is assessed using spectral fatigue analysis of ten naval vessels in a class. Four structural locations are considered. The fleet is divided into two groups: one based on the East Coast of Canada, operating primarily in the North Atlantic, the other on the West Coast of Canada, sailing mainly in the North Pacific. Unique operational profiles for each ship were developed from daily geographic locations, global seasonal wave statistics, and class-wide operating probabilities. Wave loads calculated with a frequency-domain seakeeping code were combined with linear finite element analysis to determine the corresponding stresses. Differences in fatigue damage estimates are small within each coastal fleet. The East Coast fleet experienced more severe wave conditions than their West Coast counterparts, resulting in East Coast ships having higher fatigue damage estimates. Also, fatigue damage estimates vary more in the East Coast fleet than in the West Coast fleet. Preferred speeds and headings in infrequent rough seas magnified the contributions of wave heights of 6.5 m and beyond to fatigue damage estimates.

1. Introduction

Fatigue cracks in ships are primarily caused by the cyclic stresses arising from encounters with millions of sea waves over their service lives. The desire to limit weight in naval vessels by reducing scantlings motivates the use of high-strength steels. Use of high-strength steels increases stresses, but they are acceptable in comparison to the yield strength. These higher stresses lead to fewer cycles for crack initiation since the fatigue properties of high-strength steel do not increase in proportion to their yield or tensile strength (Kirkhope et al., 1996). The operation of naval vessels in severe wave conditions and their high-strength steel construction accelerate the initiation of fatigue cracks. Sailing with compromised structure risks fully achieving mission objectives, so maintenance of naval fleets is a substantial issue, involving frequent inspections and costly repairs.

Variations in operating conditions between ships lead to different fatigue crack initiation periods. For naval vessels, the blend of missions consists of regularly-visited waters close to home and a variety of global locations that are visited less frequently. The variety of operational areas visited leads to variation in the wave environments each ship in a class experiences; this variation increases when the class is divided among multiple home ports on different bodies of water. This study uses the operational history from 1990 to 2009 for ten naval ships (five based on the East Coast of Canada, five based on the West Coast of Canada) to examine the variations in experienced wave environments and corresponding fatigue damage estimates at four structural locations. Class-wide operating probabilities were used; they include speed and heading profiles dependent on wave height. The contributions to fatigue damage accumulation of operating at different speeds or headings relative to the waves (referred to afterwards as relative heading) and at different significant wave heights are also assessed.

Fatigue damage estimates were generated using spectral fatigue analysis. Sea loads calculated with a linear frequency-domain seakeeping code were combined with linear finite element analysis to determine the resulting stress ranges. Although corrosion can accelerate fatigue crack initiation, it is not considered in this study.

The ships assessed in this study have longitudinally-stiffened displacement hulls built to Canadian Naval Standards. The global and local ship models used in this study were also used in Thompson (2016), a comparison of calculated stress spectra and associated fatigue damage estimates with those derived from full-scale measurements taken during a sea trial.

The assessed structural arrangements do not have stress concentrations or welds. They are not known or expected to have fatigue cracking problems. These simple structures are loaded predominantly by horizontal or vertical bending, although the side shell structures also experience local stiffener bending due to the wave action. The simple nature of the assessed structures provides insights that may be otherwise skewed by local stress concentrations in structures more prone to fatigue damage. Since vertical bending causes stress ranges greater than those from horizontal bending, the locations close to the weather deck and keel are of greater interest than those near the side shell close to the

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waterline. The two locations near the side shell are of less concern, but are included because more fatigue-prone structures may experience a combination of horizontal and vertical bending.

No assessments of the variation of fatigue damage within a class of ships were found in a review of the open literature. However, fatigue assessments of specific ship's components are common. In one example, Mao et al. (2010) performed spectral fatigue damage calculations of an amidships detail for a 2800 TEU container ship. They found the calculated damage had less than 10% bias compared to rainflow damage calculations using strain measurements for fourteen voyages in the North Atlantic. In another example, Andersen and Jensen (2013) found that damage calculations using spectral methods for a 9400 TEU container ship were in generally good agreement with calculations derived from long-base strain gauges.

It is common in spectral fatigue analyses to assume that relative heading angles have equal probability. This assumption is sensible in relatively benign conditions, but modifications may be required for more severe conditions. However, identifying these changes accurately may be difficult as rough conditions do not occur frequently and there may be variation in tactics and risk-mitigation strategies between operators. Ship classification societies vary in their recommended relative heading distributions. American Bureau of Shipping (2016) and Lloyd's Register (2015) suggest using equal probability headings, Bureau Veritas (2016) suggests equal heading probabilities in the absence of better information, and Det Norske Veritas (2014) does not mention the heading distribution to use. Kukkanen and Mikkola (2004) calculated the fatigue damage of a hatch cover bearing pad using spectral fatigue analysis. Uniform heading angle probabilities were used and they found that waves between 4 and 5 m high contributed the most to the accumulated fatigue damage. Although it was not included in the study, they speculated that avoidance of bad weather and high wave heights significantly affect the fatigue damage accumulation. Fatigue damage accumulated at individual wave heights was not assessed in a study of the distribution of a tanker's vertical bending moments, but Guedes Soares (1990b) mentioned that significant wave heights less than 6 m were of most concern for fatigue loading. A fatigue assessment of a butt-welded structural joint on the main deck of a tanker by Garbatov and Guedes Soares (2012) used several different relative heading distributions, none of which were dependent on wave height. Assuming continuous operations in head seas resulted in fatigue damage estimates about 20% greater than estimates using broader relative heading distributions. Another study by Guedes Soares (1990a) recognized that wave-induced loads are more sensitive to heading changes than to changes in speed. He also mentioned that voluntary course changes made in heavy weather put ships in conditions with larger bending moments.

The intent of this study is to assess how fatigue damage accumulation varies in a class due to operating in different geographical locations. Maintenance records were reviewed for comparison with the study results. Conclusions on the accuracy of calculated results could not be drawn because of several known significant omissions and differences in the recording practices of each coastal fleet. The methodology is explained in Section 2, the results are presented and discussed in Section 3, and conclusions are drawn in Section 4.

2. Methodology

Spectral fatigue analysis was used to calculate the fatigue damage accumulated at four structural arrangements for ten naval vessels. Fatigue damage is only considered from interactions with sea waves. A linear hydrodynamic code was used which assumes the seaway can be represented sufficiently by wave superposition. Increasing wave steepness reduces the accuracy of linear hydrodynamics; Buckley (1988) suggests that waves with a steepness greater than 0.05 are not accurately modeled with linear hydrodynamic methods. The hydrodynamic analysis did not include nonlinear aspects such as slamming or whipping. Including slamming and whipping would increase the fatigue damage estimates at high speeds and rough waves, however, Stambaugh et al. (2014) and Drummen et al. (2014) found their contributions were relatively small in an assessment of a hull form similar to a frigate, especially for wave heights below 4 m.

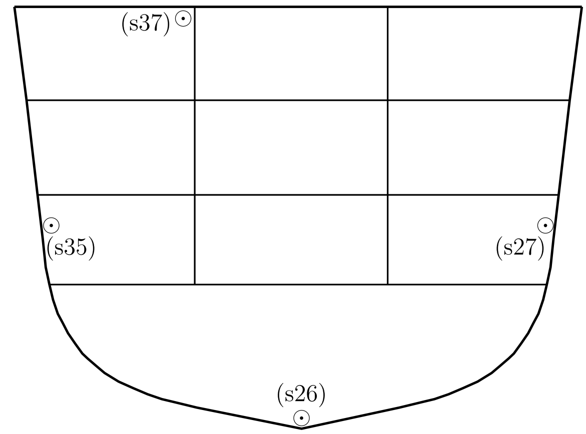

Fig. 1. Approximate locations of assessed structures.

The global and local finite element (FE) models used in this study were also used in Thompson (2016), a validation study. The structural locations assessed in this study are a sub-set of those in the prior study, including four areas near midship but excluding those near the bow where bending stresses are typically low. A hull cross-section sketch in Fig. 1 shows the approximate locations of the assessed structures.

Stress spectra and corresponding fatigue damage estimates were calculated using software developed within Cooperative Research Ships (CRS). Fig. 2 shows the whole-ship hydrodynamic model containing about 11,000 nodes and 10,000 panels. The June 2014 version of PRECAL_R (van Daalen and Sireta, 2014), a linear three-dimensional frequency domain potential flow hydrodynamic code, was used to calculate nodal forces for each combination of ship speed, relative heading, and wave frequency. Five speeds (5–25 knots in 5 knot increments), eight relative heading angles (0–315° in 45° increments), and thirty-six frequencies from 0.2 to 2.5 rad/s (0.05 rad/s increments from 0.55 to 1.55 rad/s and 0.1 rad/s increments elsewhere) were used in this study. This created 1440 unique load cases. The load cases were applied to the wetted hull of the finite element model within STRUC_R version 2.4.43 (Thompson et al., 2013), the CRS spectral fatigue analysis software. The global finite element model shown in Fig. 3 consists primarily of linear shell and beam elements. The typical mesh size is approximately one quarter of the frame spacing, resulting in about 70,000 nodes and 160,000 elements. As in Thompson (2016), top-down, or global-local, analysis was used to calculate stresses in refined local models. For each load case, global model nodal displacements were applied to coincident local model nodes along the local model boundary, referred to as master nodes. The displacements of other nodes along the local model boundaries were calculated using linear interpolation between the master nodes. The linear VAST finite element solver (Martec Limited, 2006) was used to calculate displacements and stresses for the global and local models. The local models extended, as a minimum, longitudinally to the next frames and transversely to adjacent stiffeners. There are about 900 local elements within each corresponding global element; the mesh was refined to be similar in size to the strain gauges assessed in Thompson (2016). A convergence study showed that further refinement did not change the results significantly. The local model for s26 is shown in Fig. 4. Stress transfer functions for each combination of speed and relative heading are based on the longitudinal stress.

In spectral fatigue analysis, calculated stress transfer functions estimate how the structure responds to possible conditions while the