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A comparative study of fatigue assessments of container ship structures using various direct calculation approaches

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ABSTRACT

It is common practice today to carry out fatigue assessments of ship structures using direct calculation procedures to compute fatigue loads. Many numerical codes are available for use in such fatigue load analyses. In addition to the various degrees of computation complexity associated with fatigue estimation methods, such methods also have large inherent uncertainties. In this investigation, a comparative study was carried out for two container ships using various typical direct fatigue calculation methods. The fatigue damage amounts calculated using these methods were compared with those obtained from full-scale measurements. Most of the direct calculation approaches investigated yielded similar fatigue damage estimates. The approach that employs nonlinear time-domain hydrodynamic analysis and the finite element method yields reasonable and conservative fatigue damage results and is therefore recommended. In addition, the results of this study confirm that various measures of wave environments and of the variation in wave models are important sources of uncertainty in fatigue life prediction.

1. Introduction

As manufactured goods become increasingly containerised, container ships are becoming more important in the shipping industry. The container ship fleet has expanded from 1.6% of the tonnage of the world fleet in 1980 to over 13% in 2011 (UNCTAD, 2012). The role of container ships in global trade is even more important than this tonnage share would suggest: in terms of dollars, 52% of today's seaborne trade is containerised (UNCTAD, 2012). Meanwhile, container ships are increasing dramatically in size. Since the emergence of the first container ship in the mid-1950s, five major generations of container ships have been developed, and container transport capacity has increased from less than 1000 TEU (20-foot-equivalent units) to 18,000 TEU (Rodrigue, 2013). The size of container ships is expected to continue to increase because of the driving force of scale economics.

The rapid development of container ships has created challenges with respect to fatigue design. As ships become larger, their loads increase, and the hull strength must be enhanced as a result. To reduce material costs and maximise the deadweight for load capacity, high-tensile steel has been used extensively in ship hull structures, and the steel strengths used are increasing. High-tensile steels with yield strengths as high as 470 MPa have been used in the construction of hull structures for container vessels. Given that the fatigue resistance of welded structures is not proportional to that of the base material but rather is limited by the fatigue strength of the welded joints, higher cyclic stresses along with the usage of high-tensile steel have resulted in increased fatigue damage to previously acceptable ship structural details. Moreover, although high-tensile steel is already used, thicker plates must be used in the upper hulls of container ships because of large deck openings. Thus, the fatigue strengths of deck structures with thick plating decrease due to the thickness effect. To address the increase in hull girder stress and the decrease in fatigue strength, structural details should be optimised with respect to stress concentration and fatigue loads must be evaluated with improved accuracy.

Fatigue cracks in container vessels have not been widely reported in the public literature until recently. This can be explained in part by the fact that the global container fleet is relatively young, with an average ship age of 10.7 years, which is considerably lower than the average age of other major types of ships (UNCTAD, 2012). However, container vessels do have fatigue problems. Fricke et al. (2010) reported a growing number of fatigue cracks in the side-shell structures of 10-year-old Panamax container ships. Storhaug and Moe (2007) reported the presence of serious deck cracks in container vessels after less than 8 years of service. Surveys indicated that the structural design of these ships

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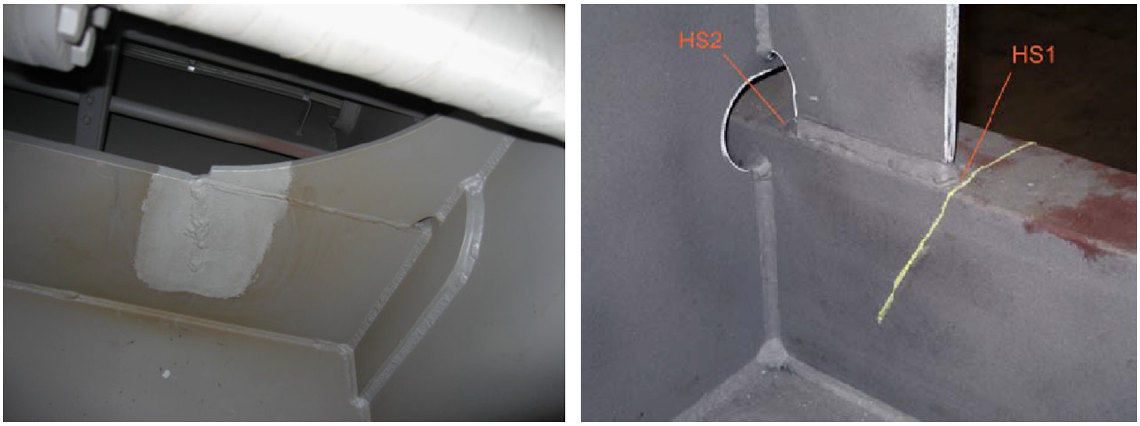

Fig. 1. (Left) Typical repaired crack on the upper inner side longitudinal below deck amidships (from Storhaug and Moe (2007)); (Right) Fatigue crack at the side longitudinal of a Panamax container vessel (from Fricke et al. (2010)).

followed regulations and that good welding workmanship was observed at the cracked joints. Fig. 1 provides examples of fatigue cracking for both of these cases. These findings justify the need for fatigue assessments of individual vessels under actual operating conditions using more sophisticated approaches with respect to wave loading representation and fatigue stress analyses.

Fatigue assessments of ship structures are typically conducted using direct calculation procedures to compute fatigue loads. In contrast to the conventional-rule design approach, the direct calculation approach considers the structural and operational features of individual vessels, which is expected to lead to an improved fatigue assessment. Numerical codes are widely employed in analyses of wave loads and ship structural responses. These codes are based on various theories with different levels of complexity. However, there is no consistent evidence that one approach is optimal in all cases. The use of different methods for the same vessel typically yields different calculated fatigue damages. Thus, a comparison is needed to rationally investigate the reliability of the commonly used fatigue analysis methods.

Several authors have investigated the accuracy of fatigue assessment of ship structural details by direct calculations. In a comparative study of fatigue strength assessment procedures coordinated by the International Ship and Offshore Structures Congress (ISSC), a case study of a deck detail of a Panamax container vessel was investigated using spectral approach, in addition to procedures used by the classification rules. The results of this comparative study were reported by Fricke et al. (2002) and Kukkanen and Mikkola (2004). The spectral approach yielded a predicted fatigue life of 5.3 years, which is remarkably short for this structural detail of known good design. The results of that case study suggest that significant uncertainties are associated with direct calculation approaches. Researchers have also conducted comparative studies of wave loads on ships. For example, Cariou and Jancart (2003) conducted a comparative study of wave-induced loads on barge ship models and found that the various hydrodynamic codes yield significantly different results. They concluded that the geometric nonlinear effects should not be neglected for high sea states. This conclusion agrees with the findings of Watanabe and Guedes Soares (1999), who compared motion and load calculations for a realistic hull shape. Although these studies focused on ship motions and loads on the hull as a whole, they provide insights into the reliability of fatigue assessment via direct calculation methodologies.

In this investigation, a comparative study of two container vessels was carried out using various typical direct calculation methods. Both vessels operate along North Atlantic routes. Deck longitudinals amidships were the focus, and the results of the fatigue damage assessments were compared with those from full-scale measurements. The objectives of this comparative study were to obtain a better understanding of the factors that influence fatigue loads on ship structures and to evaluate the uncertainties associated with the direct calculation procedures. Although this particular study concerns container vessels, it also provides insights into direct calculation procedures for fatigue in general.

2. Methodology

The direct calculation of fatigue loads on ship structures involves hydrodynamic analysis, stress response evaluation, and fatigue damage calculation. Many numerical codes are available for these types of analyses. The following sections discuss the most commonly used numerical approaches and a validation methodology.

2.1. Wave modelling

The sea surface is irregular and changes constantly. An exact mathematical representation of the wave elevation as a function of such variables as time, wind speed, and wind direction is impossible. Therefore, statistical methods must be used to quantify wave characteristics. Wave elevation records can be treated as records of a random process. For ocean waves and derived wave load processes, measurements have shown that a stationary stochastic process can be assumed over short periods of time.

In ship structural analysis practice, it is typically sufficient to use linear (Airy) wave theory for the wave model, and this theory was used throughout this study. The irregular wave time history can be decomposed into a series of component regular waves using Fourier analysis:

$$\zeta = \sum_{i=1}^{N} \zeta_i \sin(\omega_i t - k_i x + \varepsilon_i) \tag{1}$$

where ζ_i, ω_i, k_i, and ε_i are the amplitude of the component wave, the wave frequency, the wave number, and the phase of the ith harmonic wave component, respectively.

A stationary sea condition is typically described by a wave spectrum. A wave spectrum $S(\omega|H_s, T_p)$ describes the amount of wave energy at different wave frequencies and can be expressed as a function of the significant wave height H_s and, for instance, the peak period T_p. With the spectral density known, the amplitude of