Ocean Engineering 69 (2013) 24–33

Contents lists available at SciVerse ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Corrosion of high tensile steel onboard bulk carrier loaded with coal of different origins

Jian Hua *, Chih-Wen Cheng

Department of Marine Engineering, National Taiwan Ocean University, Keelung City 20224, Taiwan, ROC

ARTICLE INFO

Article history:
Received 8 August 2012
Accepted 12 May 2013
Available online 7 June 2013

Keywords:
Corrosion
Steel
High tensile steel
Bulk carrier
Coal
Cargo ship

ABSTRACT

A sudden increase in bulk carrier losses in the early 1980s caused considerable alarm in the shipping industry. This paper presents corrosion rate models for the structural components of high tensile steel (HTS) and demonstrates corrosion as affected by various factors determining the microclimate in the holds. For specimens buried in coal from Australia and Indonesia, the difference in mass loss was similar and almost negligible. Average corrosion rates for all specimens under various stress levels vary nonlinearly over time, especially during the first 48 h. Regarding the corrosion rates of specimens, generally the corrosion rates of specimens under the same stress in Australian coal were slightly higher than those of specimens in Indonesian coal between 48 and 240 h. The corrosion levels for most HTS specimens did not correspond to the ranking of stress levels they suffered throughout the experiment. The mass loss for specimens in Indonesian and Australia coal under stress levels other than 95% was similar at 2 h and 96 h. The pattern of corrosion that has been observed for steel in sand and soil also occur for fine-particle coal in this investigation. The corrosion rates of HTS covered by both coals were highly dependent on the quantity of water contents.

1. Introduction

Bulk carriers are extremely important for marine transportation. In 2010, the world's bulk carriers transported the equivalent of over 8 billion ton-miles of commodities, primarily coal, iron ore, grain, bauxite, and phosphate (International Association of Dry Cargo Shipowners, 2011). Ship sizes are increasing in response to the rapidly growing bulk cargo market, especially for coal and iron ore. Today, the world's bulker fleet includes 8687 ships of over 10,000 dead weight tonnage, representing 40% of all ship tonnage and 39.4% of all vessels (Shipping and World Trade, 2012).

1.1. Casualties and structural failure

The Lloyd's Register (LR) shipping records from 1963 to 1996 (Lloyd's Register of Shipping, 1998) recorded 355 bulk carrier casualties, which resulted in the loss of 2038 seafarers. According to the records, 125 ships foundered because of cracks and/or flooding in the cargo hold, were suddenly broken in two, or disappeared with no information on the cause.

The massive structures of large bulk carriers bend with the movement of the sea; this is known as “hogging” and “sagging.” Loading patterns can enhance the negative effects. Dense cargos, such as coal and iron ore, are frequently carried in alternate holds to moderate the roll motions, which increase the stress on inner hull components, for example, frames and girders (Lloyd's Register of Shipping, 1998). A study conducted by the International Association of Classification Societies (IACS) showed that 5% and 10% overloads on various holds increased the still water bending moment by up to 15% and 40%, and the shear force by up to 5% and 20%, respectively (International Association of Classification Societies (IACS), 1994). Extremely large hatch openings may present additional points of weakness in the hull.

A sudden increase in bulk carrier losses in the early 1980s caused considerable alarm in the shipping industry (Shipping and World Trade, 2012). The International Maritime Organization (IMO) adopted Resolution A.713(17) (“Safety of Ships Carrying Dry Bulk Cargos”), which noted that the nature of cargo and ballast operations can subject bulk carriers to severe bending patterns, sheer forces, and significant wear (IACS, 1994). The IMO, IACS, and major classification societies have subsequently established standards on the structural integrity of ships (Paik et al., 2003a).

In Lloyd's Register of Shipping (Shipping and World Trade, 2012; Roberts and Marlow, 2002), the primary cause of most casualties was concluded to be the side structure's inability to withstand the combination of local corrosion, fatigue cracking, and operational damage (Lloyd's Register of Shipping, 1998). Structural failures were because of a combination of factors, such as physical

* Corresponding author. Tel.: +886 2 24622192x7106; fax: +886 2 24633765.
E-mail address: huajian@ntou.edu.tw (J. Hua).

0029-8018/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.oceaneng.2013.05.020

damage suffered during operations (Lloyd's Register of Shipping, 1998). Statistics show that nearly 90% of ship failures are attributed to corrosion, which, without proper maintenance, can result in disasters (Roberts and Marlow, 2002; Qin and Cui, 2003). The guidelines for planning an enhanced program of inspections emphasize the importance of reducing corrosion in holds and tanks, where corrosion is extremely likely to occur (Nakai et al., 2004a).

Since 2003 ISSC has established a special committee to address the issue of structural integrity of aging structures (International Ship and Offshore Structures Congress (ISSC), 2009). Their reports covered extensively the fundamental research and theory related to environment, loads, structural responses, design methodology, analysis and evaluation, and design principles and are helpful in understanding the development and trends of condition assessment (ISSC, 2009).

1.2. Factors influencing corrosion of bulk carriers

The structural deterioration comes in various forms including coating damage, corrosion, cracking, deformations, and changes in material properties (ISSC, 2009). Melchers and Jiang (2006) presented a survey to obtain initial estimates of models for coating durability for ballast tanks. Empirical relationships were derived and found that geometric properties are linear functions of total corrosion loss (Chowdhury, 2008). Non-linear functions for corrosion loss have been proposed but with significant uncertainty and makes it difficult to assess the effect of environmental factors (Melchers, 2008). Ivanov (2009) used probabilistic methods to assess the hull girder bending capacity for a risk-based inspection planning framework.

The corrosion mechanism used in the cargo holds of bulk carriers is general wastage in steel plates, which is reflected in a generalized decrease of plate thickness (Qin and Cui, 2003). For an example, consider a case that occurred in the North Atlantic Ocean in April 2004 (Nakai et al., 2004a). A 12.5-year-old fully loaded capesize bulk carrier sustained damage that destroyed the entire side shell of its no. 3 cargo hold on the port side during the voyage from Brazil to Japan. Fortunately, the ship survived because of its strong fore and an experienced salvage team. That its sister ship sank in the same area in 2001 may not be a coincidence. The two ships were approximately the same age when the incidents occurred (Nakai et al., 2004b). The thickness of the side shell frames of the surviving bulk carrier was approximately 30% for the web plate and 50% for the face plate, and the density of the pitting corrosion was over 50% for both the lower web and face plates (Nakai et al., 2004a). The effect of pitting corrosion on side shell frames may decrease the ultimate strength and loading of shell plates by 24%, and the pitting distribution concentrated on the web plate by 54% (Andreassen et al., 1998).

A clear link between accidents and the ship age exists. Paik et al. (2004a) collected measurement data of structural wastage caused by corrosion, and quantified the characteristics of corrosion loss and rate related to ship age using statistical analysis. Aging has been perceived to be an important factor in hull damages (ISSC, 2009). In aging ships, corrosion and fatigue cracks are the two most important factors affecting structural safety and integrity (Paik et al., 2004b). According to the LR survey results, the historically critical age for bulk carrier casualties is 14–18 years (Lloyd's Register of Shipping, 1998). Since 2005, the average bulk carrier was just over 13 years old, with 41% less than 10 years old (International Association of Dry Cargo Shipowners, 2011). Corrosion and general fatigue increase with ship age primarily because of the stresses the ship is inevitably subjected to through routine voyaging, cargo handling, and the weather and waves (Lloyd's Register of Shipping, 1998). Soares et al. (2008) proposed a corrosion wastage model to measure the effect of environmental factors, including temperature, carbon dioxide, and hydrogen sulfide concentrations, on the corrosion behavior of ship steels subjected to crude oil tank atmospheres. Additionally, the severity and importance of the residual stress caused by welding operations is frequently underestimated (Andreassen et al., 1998).

Coal and iron ore are frequently removed from the hold by large grabs, bulldozers, and hydraulic hammers. Needing to accelerate this process, for reasons such as amendments to the navigation schedule, may increase the negative effects in some cases. Furthermore, coal and iron ore inevitably cause coating damage and corrosion to the hull structure of cargo holds during when loaded and unloaded. Coal causes further corrosion to damaged areas (Soares et al., 2008; Nakai et al., 2006), particularly the lower components (Nakai et al., 2006). Serious corrosion reduces the structural resistance against impacts from rough seas, and may cause further structural failures.

1.3. Bulk carriers built from high-tensile steel

Since the early 1980s, the ship building industry has increased its use of high-tensile steel (HTS), especially for bulk carriers, because the plates can be 4–9 mm thinner without losing strength (Melchers, 1997; Melchers, 1999a). However, HTS-built ships are more prone to structural problems because load is transferred through the ships' structural components, and the structural response is interdependent (Melchers, 1999b). Because ships are flexible and tend to vibrate in short sea waves, HTS ships require at least the same care and maintenance as ships built of mild steel do (Lloyd's Register of Shipping, 1998).

Gardiner and Melchers (2002a) identified three main corrosion environment types of a bulk carrier made from HTS, namely, immersion in seawater, exposure to an enclosed atmosphere, and exposure to porous media. The corrosion process of cargo holds filled with coal is similar to that of steel buried in soil. Li et al. (2007) monitored the corrosion of steel in soil environments using a thin-film electrical resistance sensor with high sensitivity. The study enabled the rapid prediction of the long-term corrosion behavior of steel, expressed using a kinetic curve obeying power law. Experimental studies on the corrosion of steel by coal focused primarily on the corrosivity of the fluid that resides within or in contact with the media (Gardiner and Melchers, 2002b; Li et al., 2007).

Most corrosion models used in previous research were based on estimations of actual measurements because the complex variables and uncertainties may influence the corrosion rate (Roberts and Marlow, 2002). The corrosion rate of every relevant structural area must be predicted to estimate corrosion tolerance. The objectives of this paper are as follows. (1) Present corrosion rate models for the structural components of HTS in large bulk carriers loaded with coal of different origin. (2) Demonstrate that the corrosion of HTS is affected by various factors possibly determined by the microclimate in the coal holds of bulk carriers.

2. Method and procedure

2.1. Steel specimen preparation

The investigation simulated the progress of corrosion on a HTS (AH36) structure buried in coal cargo from Australia and Indonesia. AH36 is widely used for structural components e.g. side shell, side shell frame, bulkhead, bottom plate, inner bottom plate, and longitudinal members. Fig. 1 shows the structural components of cargo holds considered for the corrosion study.