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Operability of non-ice class aged ships in the Arctic Ocean—Part I: Ultimate limit state approach

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ABSTRACT

Ultimate limit state-based ultimate longitudinal strength analysis was performed to identify the operability of aged non-ice class ships in the Arctic Ocean considering aging. A series of Arctic temperatures, i.e., from room temperature to −80 °C, were applied to the target structure. Time-variant corrosion wastage was employed in the case of age-related damage. The ALPS/HULL progressive hull girder collapse analysis program based on the ISFEM (Idealized Super-size Finite Element Method) was used to evaluate the ultimate hull girder strength with the material properties determined from a series of tensile tests. Based on the results, the operability of aged ships operating under Arctic conditions was estimated.

1. Introduction

Recently, the Arctic region has become an attractive region. Owing to global warming, the extent of Arctic ice has decreased enough to allow more offshore activities and shipping in Arctic regions. Approximately 13% of undiscovered natural fossil resources in the Arctic region are becoming practicable. Moreover, there are some advantages in using the Northern Sea Routes (NSR) for shipping, i.e. shorter sailing distance, less fuel spend, reduction of carbon dioxide emission and high earning, as shown in Table 1.

On the other hand, the IMO (International Maritime Organization) Guidelines (IMO, 2011) for ships operating in polar waters recommended that only those ships with a Polar Class designation, which were assigned based on the IACS Unified Requirements for Polar Class Ships (UR-I) (IACS, 2011), or a comparable alternative standard of ice-strengthening appropriate to the anticipated ice conditions, should operate in polar ice-covered waters. The UR-I was applied uniformly by IACS societies to ships that were contracted for construction on or after the 1st March 2008.

To cope with the rising demand for operating in the Arctic ice-covered region, existing ships with a Polar Class designation are lacking. New vessels satisfying the Polar Class designation require time with the cost for a new design and construction. Moreover, the amendments to MARPOL Annex VI (IMO, 2011) on CO_2 emissions were adopted by the IMO in July 2011 and will enter into force in 2013 to control the CO_2 emission from shipping. The IMO developed the first ever global CO_2 reduction index in the world, which is known as the EEDI (Energy Efficiency Design Index). The regulations for new ships are reinforced.

NSRs are estimated to be open for transit voyages for two to four months per year during the early autumn (NORDIC, 2010). During the season, the typical ambient temperature is over 0 °C and floating icebergs are smaller than in winter season.

Furthermore, polar pack ice is not perfectly continuous, and it always has 1–5% of open lead or shallow ice less than 30 cm in thickness (Sanderson, 1988). The open lead is 10 to hundreds of meters in breadth. Ship navigation would be possible with a good observation system without an additional ice load on the hull of ships without a Polar Class designation.

In this regard, a study on the existing non-ice class vessels in terms of the strength capacity was undertaken on the operability in the Arctic region.

2. Operating condition

2.1. Arctic Ocean environment

The operating conditions of general ships through the normal route are different from Arctic sea going vessels. Ships and offshore structures operating in the Arctic region are exposed to poor weather conditions, as shown in Table 2. Extremely low temperatures (−50 °C) and a maximum ice thickness of 2.5 m can affect the ship hull during winter (Emmerson and Lahn, 2012).

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Table 1
Distances and potential days saved for Asian transport from Kirkenes (Norway) and Murmansk (Russia) (Emmerson and Lahn, 2012).

Destination	Via Suez Canal			Through Northern Sea Route			Days saved
	Distance (N m)	Speed (kn)	Days	Distance (N m)	Speed (kn)	Days	
Shanghai, China	12,050	14	37	6500	12.9	21.0	−16.0
Busan, Korea	12,400	14	38	6050	12.9	19.5	−18.5
Yokohama, Japan	12,730	14	39	5750	12.9	18.5	−20.5

Table 2
Current winter and summer conditions along the Northern Sea Route (Emmerson and Lahn, 2012).

Region	Kara Sea	Laptev Sea	East Siberian Sea
Winter season	Oct.–May	Oct.–June	Oct.–May/June
Temp. typical	−26 °C	−30 °C	−21 °C
Temp. extreme	−48 °C	−50 °C	−48 °C
Ice thickness	1.8–2.5 m	1.6–2.5 m	1.2–2.0 m
Fog	100 days	75 days	80 days
Summer season	June–Sept.	July–Sept.	Mid June–Sept.
Temp. typical	7 °C	8 °C	15 °C
Temp. extreme	20 °C	26 °C	30 °C

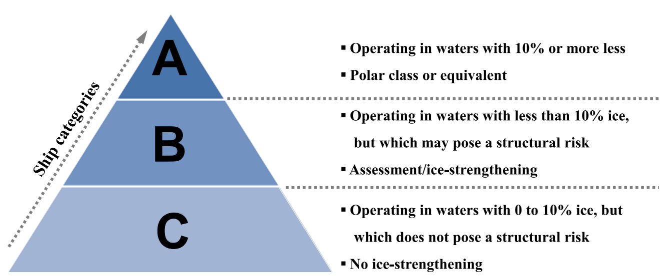

Fig. 1. Categories of ships operating in polar waters (Deggim, 2011).

2.2. Polar class description

Despite the IACS Unified Requirements for Polar Class Ships (UR-I), which divides the polar class into 7 classes depending on the operating season and ice condition, the IMO divides ships in polar water (Fig. 1) based on water condition and structural risk. Although all IACS Polar Classes consider the ice load, ships with both a Polar Class designation and C-class can operate in the Arctic oceans through the open leads in the IMO ship categories.

3. Ultimate hull girder strength analysis

In this study, a Suezmax class double hull oil tanker was analyzed in terms of ultimate limit state over a series of temperatures to identify the operability of non-ice class vessels on the NSR. The analysis method and material properties should be defined when examining the effects of low temperatures on the ultimate hull girder strength performance, the level of in-service damage and time-dependent corrosion wastage. Therefore, in this study, the above-mentioned factors were examined and ultimate hull girder strength analysis was performed considering Arctic conditions.

3.1. Corrosion wastage model

Ships and offshore structures operate in the ocean for at least 70% of their lifetimes. During this period, aging problems associated with corrosion, fatigue cracking and localised denting will naturally occur (Paik and Thayamballi, 2007). Among them, to protect the structures from corrosion damage, some management procedures are mainly applied in ship design (Paik and Melchers, 2008), such as corrosion addition, coating, cathodic protection, ballast water deoxygenation and chemical inhibitors. In particular, the corrosion addition margin method is generally applied to ships and offshore structural design.

In regard to this problem, a number of designers have attempted to define the reliable corrosion addition values to protect the structures from corrosion damage. Many studies have examined the effects of corrosion on the structural behaviours of ship structures (Paik et al., 2009; Gudze and Melchers, 2008), offshore structure (Melchers, 2005; Zhang et al., 2010) and subsea structures (Bai and Bai, 2010; Xu and Cheng, 2012; Chaves and Melchers, 2011).

In the case of ship design, the CSR (Common Structural Rule), which specifies the uniform corrosion additions for oil tankers and bulk carriers, was adopted at the ship design state. Some application studies were performed on ship structures to identify the effects of the corrosion addition rules (Paik et al., 2009; Kim et al., 2012a,b,c).

On the other hand, the corresponding values are not accurate because they are not based on real measured corrosion data. In this regard, the time-variant corrosion wastage model has been proposed. Paik et al. (2003a, 2003b, 2004) proposed an innovative method to predict the more refined corrosion wastage considering time for ocean structures. This was called the time-variant corrosion wastage model. Other approaches in terms of the time-variant corrosion wastage were also reported (Qin and Cui, 2003; Guo et al., 2008). Recently, Paik and Kim (2012) performed advanced approaches in developing the time-variant corrosion wastage model.

The selection of an appropriate corrosion model is an important procedure for estimating the coating life. In the present paper, the time-variant corrosion wastage model of double hull oil tankers by Paik et al. (2003a) was applied by considering the 10 years assumed coating life. This study considered 10, 15, 20, and 25 years of time variant relations. Fig. 2 presents the applied time-variant corrosion wastage model (Paik et al., 2003a).

3.2. Material model

A series of material coupon tensile tests were undertaken at low temperatures on the grades of carbon steel ASTM A131 (Park et al., 2013). Pin-loaded, dog bone shaped tension test specimens with a 50 mm gauge length specified in the ASTM E8/E8M standards (ASTM, 2004) were tested according to the ISO 15579 (2000) standards (ISO 15579, 2000). The specimens were cut from a plate in the longitudinal direction. A liquid nitrogen-cooled environment chamber system was used, as shown in Fig. 3. During the tests, the temperature of the specimen and the ambient temperature inside the chamber were kept from going below the target temperature. A 1000 kN actuator moved quasi-statically (0.05 mm/s (0.001 s^{-1}) for room temperature and 0.015 mm/s (0.0003 s^{-1}) for low temperatures) as a loading, and a 200 kN load cell and extensometer measured the load and the change in the gauge length every 0.1 s.

Generally, the yield strength from material tensile tests is higher than the minimum requirement of the material rule. On the other hand, the minimum yield strength is used in ultimate strength analysis to determine a pessimistic view. Fig. 4 shows increasing ratios of the yield strength at low temperatures on the grades of ASTM A131 steels. Similar increase ratios were observed on mild steels and high tensile steels except for Grade A mild steel, which is a non-ice class material in IACS Polar Class. Approximately 31.7% for Grade A, 21.4% for polar classed MSs (Grade B and D) and 13.9% for HTs were observed at −80 °C.