ABSTRACT
An accurate estimation of corrosion rates plays an important role in determining corrosion allowances for structural designs, planning for inspections, and scheduling for maintenance.

This paper presents an estimation of corrosion rates of structural members in oil tankers based on a corrosion wastage database of over 110,000 thickness measurements from 140 single hull oil tankers. Corrosion rates may be described by a Weibull distribution function. Mean, standard deviation and maximum values of corrosion rates for structural members are obtained based on the entire population of the database. They are compared with the ranges of corrosion rate published by Tanker Structure Co-operative Forum (TSCF).

The study aims to update knowledge on corrosion rates in steel ships, and to contribute to the efforts of mitigating the risks of corrosion.

INTRODUCTION
Corrosion is a major cause of marine structural failures. Corrosion results in loss of structural strength at local and global levels, and leads to fatigue failure and stress corrosion cracking. Some recent marine incidents with tankers have been directly linked to accelerated corrosion.

The annual corrosion related costs to the U.S. marine shipping industry is estimated at $2.7 billion. This cost is divided into costs associated with new construction ($1.12 billion), with maintenance and repairs ($810 million), and with corrosion-related downtime ($785 million) (Johnson 2001).

Classification Societies have established safety standards requiring that structural scantlings of marine structures be designed with allowances for corrosion wastage. These initial design allowances are based on corrosion wastage expected during the service of ships under normal operation and maintenance practices.

Steel is often coated with paint, and sacrificial anodes are fitted at some locations. These serve to reduce and in some instances effectively defer corrosion and mitigate corrosion consequences.

Ships in service are periodically surveyed and inspected. If corrosion is found, wasted plates are recommended to be renewed. Decisions regarding the extent of renewal require the knowledge of how much more the steel will corrode before the next inspection.

Surveyors also inspect the condition of coating (ABS 1998). Substantial corrosion is noted and more frequent inspections may be required to ensure that substantial corrosion will not threaten the structural integrity of the ship. If coating breakdown is found to be in poor condition, annual surveys are required.

Accurate estimation of corrosion rates is therefore required for initial structural design, inspection planning and maintenance scheduling. This information is very important for planning the economic life of a ship.

There are limited research and corrosion measurement data available for corrosion rates in tankers. Discussions on corrosion wastage remain largely qualitative rather than quantitative.

This paper estimates the corrosion rates of structural members in oil tankers using a probabilistic model and a corrosion wastage database (Wang et al. 2003). Mean and maximum corrosion rates are presented. These values are compared with TSCF (1992) recommendations, and general trends are discussed.
This paper aims to update the knowledge on corrosion rates in oil tankers, and to contribute to the efforts of mitigating the risks of corrosion.

CORROSION IN OIL TANKERS

Figure 1 shows the corroded bulkhead in an oil tanker. Corrosion of steel plates is a complex phenomenon that is influenced by many factors. Various corrosion mechanisms exist in any particular location. For example, the under-deck area is subjected to sweet or CO₂ corrosion, and sour H₂S or sulfur corrosion. Steel may be uniformly wasted (general corrosion), or may be corroded in localized areas (pitting or grooving). The attention of this paper is placed on general corrosion, where steel plates are uniformly wasted. Pitting corrosion is often not fully reflected in thickness measurement reports, and is not discussed in this paper.

Factors that influence corrosion may include (Melchers 2001, Paik et al. 1998):
- Coating type and longevity
- Coating application and surface preparation
- Corrosivity of the product
- Inspection and maintenance strategies
- Cathodic protection
- Trade route

This is only a partial list. Many factors interact with others, complicating the problem further.

There is an ongoing interest in developing models for predicting corrosion wastage (Gardiner and Melchers 2001). Phenomenal models have the advantage in quantitatively estimating definable corrosion mechanisms, but are often confined to limited groups of cases. Their effectiveness is still not fully demonstrated.

There is a high variability in corrosion wastage (e.g., TSCF 1992, Loseth et al. 1994, Melchers 2001, Wang et al. 2003, Paik et al. 2003). Statistical analysis on a collection of corrosion measurements seems to be one of the best options to express corrosion rates in oil tankers.

EXISTING MODELS FOR CORROSION WASTAGE IN STEEL SHIPS

Figure 2 shows schematically the available models for corrosion progress published to date. These models are used for assessing structural conditions. They do not address the mechanics of corrosion.

Typically, it is assumed that corrosion does not take place when a coated structure is first placed in service. Usually, this is the period before the coating breaks down and loses effectiveness in protecting the steel. After that, corrosion begins, and wastage increases over time.

For the second stage of corrosion, there are three types of models for corrosion progress:
- Corrosion wastage linearly increases with time (line a). This is perhaps the most common and most widely used assumption in structural strength analyses.
- Corrosion increases and accelerates over time (line b). This occurs when rust build-up is disturbed if a structure flexes under the wave action (TSCF 1992, Saidarasamoot et al. 2003).
• The rate of corrosion wastage slows down with time (line c), when the steel is gradually covered by scale
• and rust, preventing further exposure of new steel to corrosive environment.
• As a variation of line c, corrosion wastage eventually approaches a plateau, which remains constant.

These models have advantages and disadvantages. They may be good for some, but not all situations.

Corrosion rate is the slope of the lines in Fig. 2. Obviously, the corrosion rate in existing models can be:

• Constant, or
• Not constant, changing over time (lines b and c).

Melchers (2001) treated the mean values and standard deviations as separate parameters, and tested linear, bi-linear and power models for each of them.

Yamamoto and Ikeyama (1998) described a corrosion mechanism based on pitting initiation and growth. Different probability functions were assumed for the three stages: deterioration of coating, pitting initiation, and pitting growth. Their models were calibrated with measurement data of bulk carriers, and later applied to oil tankers (Harada et al. 2001)

Paik et al. (1998, 2003) assumed no corrosion for about 5 to 10 years, and a constant corrosion rate for the remaining life of the steel. They assumed that the coating life follows a normal distribution and the corrosion rate follows a Weibull distribution. Parameters of these models are derived from data on corrosion measurements.

Guedes Soares and Garbatov (1999) used a 3-stage corrosion model. The corrosion rate starts at zero when the coating is effective, increases when the steel loses protection from the coating, and becomes zero again when rust covers the steel. This model is flexible and can adapt to many situations once the long-term corrosion wastage and the duration of the corrosion process is known.

There are also studies on the influences of different corrosion models on the time variant reliability of both local structural members and hull girders (Ivanov et al. 2003).

ESTIMATION OF CORROSION RATES

There are three major components in the analysis of corrosion rates of structural members:

• Probabilistic representations
• Corrosion rate models
• Corrosion wastage databases

The high variability observed in corrosion wastage of structural members requires proper consideration of the uncertainties. A probabilistic presentation may be preferable. A constant-rate corrosion progress model is used in this study (line a in Fig. 2). A complex corrosion model is avoided. The additional complexity introduced by more refined mathematical models has yet to prove the value of such an approach in improved prediction accuracy. Detailed modeling of the changes in structural thickness over time is left to further development.

For simplicity, it is assumed that there is no corrosion during the first five years of service. This coating effective period should also be treated using a probabilistic model, as this is known to vary depending on different situations. This topic is not pursued in this paper, and will be investigated in the future.

Figure 2. Existing models for corrosion progress

Figure 3. Frequency distribution of corrosion rate for deck plates in cargo tanks (based on 4665 measurements)
The latest corrosion wastage database (Wang et al. 2003) provides a wealth of corrosion wastage data representing corrosion in single hull oil tankers. It is another contribution to the knowledge of corrosion in oil tankers since the Tanker Structure Co-operative Forum published their collective studies on corrosion in 1992 (TSCF 1992). Main details of this database are shown in Appendix A. The database is used here to derive corrosion rates.

Figure 3 is the density histogram of corrosion rates of deck plates in cargo tanks. This is based on 4665 thickness measurements from 140 single hull tankers. The tankers were 168 to 401 meters in length, and were 12 to 32 years old when the measurements were taken. See also Fig. 4 of Wang et al. (2003) and Appendix A.

From Fig. 3, it seems that for the population in the database, the corrosion rate of deck plates in cargo tanks can be described using a Weibull distribution. Two parameters are needed to define a Weibull distribution function. These are scale and shape parameters, and can be derived via curve-fitting techniques.

RESULTS AND DISCUSSIONS
Table 1 summarizes the estimated mean, standard deviation and maximum value of corrosion rates for
various structural members in single hull oil tankers. The calculations are based on all measurements of the database. No consideration is given to age and size of ships.

Some observations are listed here:

- Corrosion rates scatter in wide ranges. The standard deviations are comparable to, or even higher than the averages.
- The maximum corrosion rate is much higher than the average.
- The average corrosion rates do not seem to depend on usage spaces (cargo or ballast tank).

The above conclusions are based on the analyses on the entire population of the corrosion wastage database. Note that these conclusions are very similar to those observed on corrosion wastage presented by Wang et al. (2003).

These conclusions from Table 1 may be generalized to the tanker fleet in the world, and can be used as reference when planning maintenance and inspection for a group of ships. Cares should be taken, however, when attempting to apply Table 1 to a specific ship, where the cargoes it carries are normally known, and the maintenance is well controlled.

Analysis using more refined models that take into account influential parameters will be reported in future papers.

Table 1 also contains the range of corrosion rate published by TSCF (1992). These data are based on the in-service corrosion rate survey questionnaire distributed to all members of TSCF. The collected data represents the empirical information of owners and classification societies for the three decades prior to 1992.

The TSCF (1992) corrosion rate ranges are considered to be conservative reflecting a high standard of maintenance carried out by the owner members. Because of the representation of the members in this Forum, the TSCF (1992) publication has been widely used in the shipping industry, and is generally regarded as a reliable source regarding corrosion in tankers. Some later developments of inspection and maintenance schemes are based on the recommendations in this literature.

The corrosion rates of TSCF (1992) on cargo oil tanks and segregated ballast tanks are listed in Table 2, along with those estimated in this paper on cargo tanks and ballast tanks, respectively.

Direct comparisons between Table 1 and TSCF (1992) are very difficult, because TSCF does not fully document how its members determined the corrosion rates. Still, some interesting conclusions may be drawn from Table 1:

- In general, the estimated mean corrosion rates are higher or close to the high end of the ranges of TSCF (1992). This may be due to the fact that the sampled ships of TSCF were better maintained.
- The estimated maximum corrosion rates are much higher than TSCF. The TSCF ranges might not capture extreme cases.
- Both show that corrosion rates scatter. The TSCF range of corrosion rate is wide; and the estimated standard deviation of corrosion rate is large and comparable to the estimated mean values.
- Instead of a range, TSCF gives a single value for some structural members, e.g., side shell plates in cargo tanks. The present estimation may be used to develop ranges of corrosion rates that supplement the studies by TSCF (1992).

The database does not include scraped ships (Wang et al. 2003). The estimated corrosion rates may not reflect the worst cases.

As the analysis is based on averaging corrosion wastage over time, corrosion rates higher than the estimations in Table 2 should be expected.

CONCLUSIONS

The corrosion rates of some structural members in single hull oil tankers are estimated. The analyses are based on a recent corrosion wastage database that contains over 110,000 thickness measurement results. Corrosion rates may be described by a Weibull distribution function. Mean, standard deviation and maximum values for corrosion rates are obtained for structural members based on the entire population of the database.

Comparisons of the estimated corrosion rates with TSCF (1992) ranges are attempted. The estimations of mean corrosion rates are generally higher than, or close to the high end of the TSCF ranges.

The estimated corrosion rates may be used for establishing corrosion allowances for structural designs, planning for inspections, and scheduling for maintenance (Wang et al. 2003).

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REFERENCES
ABS, 1998, Guidance notes on the application and maintenance of marine coating systems, American Bureau of Shipping.

APPENDIX A. A CORROSION WASTAGE DATABASE
The main details of the wastage database of Wang et al. (2003) is described in Table A.1.

<table>
<thead>
<tr>
<th>Ship type</th>
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<td>Data sources</td>
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<td>Vessels</td>
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<tr>
<td>Gauging reports</td>
<td>157</td>
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<tr>
<td>Thick. measurements</td>
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<td>Info. Hull strength</td>
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<td>Ship size</td>
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<tr>
<td>Service years</td>
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<tr>
<td>Class</td>
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<tr>
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<tr>
<td>Ship measured</td>
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