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Tensile strength assessment of corroded small scale specimens

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ABSTRACT

Tensile strength tests are performed on small scale corroded specimens, so as to derive their mechanical properties. The specimens were cut from a box girder that was initially corroded in real sea water conditions. As a result of the tensile tests the mechanical properties of the specimens are determined, namely modulus of elasticity, yield stress, tensile strength, resilience, fracture toughness and total uniform elongation. Regression equations are derived for the properties as a function of the degree of corrosion degradation. It is identified that those material parameters are influenced by the severity of corrosion degradation.

1. Introduction

Corrosion is one of the most important types of damage in aging ship structures, which leads to surface roughness, reduction of the plate thickness and strength and eventually to leakage.

The following environmental factors could be summarized as the most important ones affecting the corrosion rate of the immersed hull steel after the coating breakdown [1,2]: seawater temperature – it affects the corrosion rate in all possible stages of the corrosion process and it is the main factor determining the duration of different corrosion stages; concentration of dissolved oxygen; water pH (if outside the range 5–10), salinity (conductivity) – assists in developing the rapid rates of marine corrosion.

In addition, redox conditions and water hydrodynamics determined as near as possible to the corroding metal surface effect the corrosion rate in the Microbially Influenced Corrosion (MIC) stage (i.e., the stage of higher corrosion compared to the corrosion in the diffusion-controlled stage) [3]. Cyclic redox conditions facilitate the MIC. Other factors known as important for microbial activity, such as pH, salinity, nutrients and biocides availability could be very site-specific or could not differ too much from "average" values for seawater and bio-films growth in constructional steel. Changes in redox conditions can also lead to preferential corrosion of heat affected zone and/or weld zone.

The relative humidity and temperature variations lead to cyclic wet and dry periods, the so called wet–dry cycles. The wet–dry cycles are a critical feature of corrosion as the alternating wet and dry periods drastically change the rusting mechanisms from those obtained in bulk aqueous corrosion. Earlier studies have shown that during a wet–dry cycle, the atmospheric corrosion of low alloy steel can be divided into three stages; wetting stage, wet stage and drying stage. The corrosion rate and the rust layer modifications are thus correlated to the number and frequency of the wet–dry cycles. A detailed description and modelling of the corrosion mechanics through each of these stages and brief survey of related studies is given in Refs. [4,5].

Loss of mechanical properties may be the consequence of chemical inclusions and of surface defect. Steel can lose its ductility and strength in a wet H_2S environment as a consequence of hydrogen embrittlement phenomenon [6]. Study of pipeline steels used in the exploration and transportation of oil and gas that are exposed to such environment reported considerable degradation of mechanical properties, similar as those reported in the present paper [6]. Strength degradation is the consequence of the decrease of the local atomic cohesive force in the presence of hydrogen. Although such study can potentially be important for deck plates of oil tankers where high concentration of H_2S could appear [7], specimens studied in the present paper are corroded in seawater conditions where inclusions of hydrogen atoms are not evident. Consequently, it is still not possible to distinguish chemical and surface defect causes of loss of mechanical properties reported in the present paper.

Surface defects are manly caused by pits that are formed in addition to the uniform corrosion, causing local stress concentrations that then may cause structural cracking. Development of the plastic zone around a pre-existing corrosion pit on the steel pipe is studied in Ref. [8], dealing with the possibility of loss of pipe

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wall in the immediate area of the pit. Structural strength of flat plates with corrosion pits, as well as consequences on the strength of ship hull structures is studied in Ref. [9].

It is important to note here that some of the corrosion data reported in Refs. [10–18] are based on experimental tests of unloaded specimens and differ from the corrosion data of structural components subjected to time variant load. It is necessary to highlight, also, that using data from different sources and pooling them is a process that is liable to have large uncertainties, as the data has been produced by various authors in different conditions.

Corrosion in ship structures has an important role in the long-term structural integrity. Under conditions of high temperature, inappropriate ventilation, high stress concentration, high stress cycling, very high rates of corrosion can be achieved in spaces such as ballast tanks and at specific structural details such as horizontal stringers or longitudinal and web frames. This has been a source of concern by ship operators and classification societies that have collected much service data [19–22]. Different models have been proposed to explain the growth of corrosion wastage in ship structures combining in general some considerations about the physics of corrosion growth with the fitting of service data [19,20,23–25].

Depending on the location of the ship structural elements the corrosion rate characteristics are different and models have also been proposed that account for the effect of environmental factors on the growth of corrosion [7,26,27]. Corrosion has clear consequences in degrading the ultimate strength of ship structures [28–31] and also affecting the fatigue strength with the resulting increased level of stresses [32–34] and also by the direct degradation of fatigue strength as studied in Ref. [35].

Since the phenomena of corrosion deterioration of structural members are the consequence of extremely complex phenomena governed by many factors, it is necessary to establish corrosion margins and permissible corrosion levels by taking into account past records. An average annual corrosion rate obtained by dividing the thickness reduction of an aged member by a ship's age at a given time has conventionally been used as the basic criteria [21,22], due to the ease of assessing and handling, but more rational criteria based on a probabilistic model are needed.

In a recent work box girders have been corroded in sea environment [36] and then have been tested up to ultimate strength, showing an important reduction of strength [37] as compared with uncorroded structures. The analysis of the results suggested that this might have been the result of changes in mechanical properties of the corroded steel [30], which has suggested that this may also occur with the fatigue strength.

The work presented in Ref. [35] has demonstrated that the severe corrosion degradation of a stiffened panel may reduce the fatigue strength from FAT 100 to 65 MPa as a result of the crack propagation starting from corrosion pits and due to changes in mechanical properties of the corroded steel.

However, it has been shown that sister ships can experience different levels of corrosion, showing that the application of such models represent average situations but can have significant deviations when applied to one specific ship [7,26,27]. Furthermore, experience has shown that even in the same ship corrosion rates vary significantly from location to location. The reason is that the environmental conditions that are present in the different ship spaces and which different ships are subjected are different. Literature reviews in Refs. [1–3,38,39] have identified the main corrosion mechanisms that can be found in ship structures and the main environmental factors that affect them.

It has been recognized that corrosion is a very complex phenomenon and influenced by many factors. Describing the key material parameters as a function of the degree of corrosion deterioration may be achieved through statistical investigations (regression analysis) of specimens cut from corroded ship structure. There is a need to develop models of principal material descriptors based on the degree of corrosion degradation of steel ship structures and to use them in structural analyses for more proper prediction of the failure modes.

Corrosion studied in the present paper may be described as rather non-uniformly distributed general corrosion. Thus, effects of pitting and general corrosion are combined, as is the case on the real ship structures. Similar as in ship structures, local pits developed on corroded specimens are irregular in shape, depth and position and may therefore be considered only by means of statistical methods. Although it would be useful to consider all these effects separately, the particular value of the present study is that it combines several effects that reflect the real ship plates and the results therefore may be useful in practical ship structural design and reliability analysis of aged ships. It should be clarified that structural analysis procedures used nowadays are not considering the degradation of mechanical properties of the steel on aging ships. The effect of corrosion is only considered by reducing as-built thickness of structural elements. As demonstrated in the present paper, however, such approach may be rather unconservative. Therefore, if the findings elaborated in the present paper proof to be true, it may have significant practical consequences in ship structural design and analysis and in particular in safety evaluation of aging ships.

The work presented here analyses small scale corroded specimens, which were firstly corroded and then tested under uniaxial tensile load. The non-corroded specimens are identified as 235 MPa tensile strength and 206 GPa of Young modulus. The surface of 19 corroded specimens was analysed to identify the residual plate thickness. Mechanical properties of specimens, namely modulus of elasticity, yield stress, tensile strength, resilience, fracture toughness and total uniform elongation are analysed and regression equations are derived as a function of the corrosion degree of degradation. An equivalent stress–strain curve of corroded steel plates as a function of the corrosion degree of degradation is also constructed.

2. Corroded test specimens

The tensile test specimens have been cut from box girders that have been subjected to corrosion, in a real corrosive environment in direct contact with sea water. The dimensions of the box girder specimen were $1400 \times 800 \times 600$ mm. The box girder was made of normal shipbuilding steel with yield stress of 235 MPa, tensile strength of 400 MPa, total uniform elongation >22% with the Young modulus of 206 MPa. The chemical components of the steel used for constructing the box girders are presented in Table 1 as weight percentage.

The box-girder specimen was exposed to the Baltic seawater, which was then heated and tested in hot water. The box girder was placed in a large tank and seawater was pumped into the tank continuously. The temperature of sea water was increased and additionally oxygen depolarization sub process rate was increased

Table 1
Chemical composition of steel.

Element	Concentration, wt.%	Element	Concentration, wt.%
C	0.079	P	<0.001
Mn	0.612	S	0.00133
Si	0.017	Cr	0.0115
Cu	0.0474	Ni	<0.001
Fe	Remainder		