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Fatigue strength experiments of corroded small scale steel specimens

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ABSTRACT

The objective of this work is to analyze the fatigue strength of small scale corroded steel specimens. The specimens were cut from a box girder, which was initially corroded in real sea water conditions. The surface of 11 corroded specimens was analyzed applying photogrammetry techniques and a description of an idealized corroded surface was established. The non-corroded specimens are identified as FAT 86 category but the fatigue test demonstrated that due to the severe corrosion degradation the experimental fatigue results of the corroded specimens are located above the fatigue design category FAT 50 and below FAT 100 referring to the nominal stress approach. The regression analysis of fatigue test results leads to $m = 3.094$ and $\Delta\sigma_{97.7\%,m=3} = 64.95$ MPa. Fatigue assessment of crack propagation on a pit like crack flow based on a failure assessment diagram was performed. The admissible initial idealized flow defect has been defined, which matches the fatigue life achieved by the fatigue test for different load categories and corrosion degradation level.

1. Introduction

Corrosion and fatigue cracking may be the two most important types of damage in aging ship structures, which lead to surface roughness, reduction of the plate thickness and strength and eventually to leakage.

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 longitudinals and web frames. This has been a source of concern by ship operators and Classification Societies that have collected much service data [1–4]. 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 [3–7]. 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 [8–10] .

Corrosion has clear consequences in degrading the ultimate strength of ship structures [11–13] and also affecting the fatigue strength by the resulting increased level of stresses [14–18] and also by the direct degradation of fatigue strength as studied in this paper.

Since the phenomena of corrosion deterioration of structural members are the consequences 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 [1,2], due to easy of assessing and handling, but more rational criteria, assessing it with a probabilistic model is needed.

Fatigue is an important design criterion for welded components and global structures. The fatigue damage may even further reduce the structural strength due to the presence of different kind of imperfections, which can lead to local increase of the stresses and to an acceleration of fatigue crack initiation and propagation. For fatigue life assessments different procedures have been developed based on databases of the fatigue behavior of welded structural components as a result of both tests and theoretical investigations [19].

The main steps in fatigue analysis are based on direct calculations that involve the description of the wave induced loading [20] the stress distribution in the structure [21], the model of fatigue damage (S–N approach) or fracture mechanics approach [22] and the probabilistic evaluation of the different steps to arrive at a safety index or time dependent reliability as has been developed in [23].

The analysis of stresses is a complex task due to the complexity of a ship structure. Nowadays the method that is mostly acceptable and spread for analysing a complex welded structure is the hot spot stress approach [24] based on the effective notch stress approach [25,26]. Recommendations for fatigue stress assessment can be found in guidelines [27–29].

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However, ship welded structures are not perfect and their behavior depends on a variety of influential factors, namely geometric [30] and material properties [31], loadings, initial or post built imperfections, deterioration, crack propagation denting etc. The imperfections change permanently the structural capacity of welded structures that initially have been designed to resist loadings, keeping a certain level of safety.

In a recent work box girders have been corroded in sea environment [32] and then have been tested up to ultimate strength, showing important reduction of strength [33]. The analysis of the results suggested that this might have been done by changes in mechanical properties of the corroded steel [34], which has suggested that this may also occur with the fatigue strength. Thus, the objective of this work is to analyze the fatigue strength of corroded small scale steel specimens that have been cut from those tested box girder specimens.

Corrosion environment drastically reduces fatigue strength with respect to dry air conditions. There are important differences in the results of separate and simultaneous action of corrosion environment and fatigue load. Fatigue strength can be drastically reduced if the steel detail is first corroded and later tested in dry air condition and in this case the fatigue S–N curve may have a horizontal sector in the high frequency regime. In the simultaneous application of corrosion environment and fatigue cyclic load, the fatigue strength is drastically reduced and the fatigue S–N curve is lower and parallel to the non-corroded one.

Fatigue damage in corrosion environment is accompanied by the appearance of many cracks, but only one of them will reach the size of failure. In aged structures, the corrosion degradation initially is smoothing the existing sharp corners on hot spots and latter due the penetration effect of corrosion, new hot spots are created leading to faster fatigue damage.

The work presented here is analysing a small scale specimen of a transversely stiffened welded plate, which was firstly corroded and then fatigue tested. The surface of 11 corroded specimens was analyzed applying photogrammetry techniques to obtain the description of the corroded surfaces. The non-corroded specimens are identified as FAT 86 fatigue design category. The admissible initial flow defect has been defined, which matches the fatigue life achieved by the fatigue test for different load categories and corrosion degradation.

2. Corroded test specimen

As indicated, the fatigue specimens have been cut from box girders that have been subjected to corrosion, in a real corrosive environment in direct contact with sea water.

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		

The dimensions of the box girder specimen were 1400 × 800 × 600 mm. The deck panel was stiffened with five longitudinal flat bars with a spacing of 150 mm. The side panel was stiffened with two stiffeners on a distance of 300 and 500 mm respectively and the bottom panel was stiffened with one stiffener in the middle as may be seen in Fig. 1. The box girder was made of normal shipbuilding steel with yield stress of 235 MPa. The chemical components of the steel used for constructing the box girders as weight percentage is presented in Table 1.

The box-girder specimen was exposed to the Baltic seawater 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 by the agitation of seawater, which resulted in a corrosion rate increase.

To model corrosion degradation, acceleration anodic polarization of the metal surface was used. Anodic electric current was supplied by an external source. The test duration was 90 days without polarization. More detailed information about the corrosion set up may be seen in [32]. The total weight loss observed was 56 kg (23% of initial weight). The average value of the electrolyte flow rate was 308 dm^3/h, water temperature is 48 °C and pH = 7.93.

After the test was completed the box girder was covered with iron corrosion products. This box girder has been subjected to ultimate strength tests as described in [33–35]. Eleven fatigue test specimens were cut from the box girder from the side shell panel around the neutral axis of the box girder (see the locations marked in Fig. 1). The shape of the specimens can be seen in Fig. 2.

3. Photogrammetry analysis of corroded surfaces

To properly characterize the test specimens an analysis of their thickness has been made employing photogrammetry techniques. The photogrammetry techniques have already been used in various cases for close-range measurements, including for structural test specimen. The principles of photogrammetry are known since the

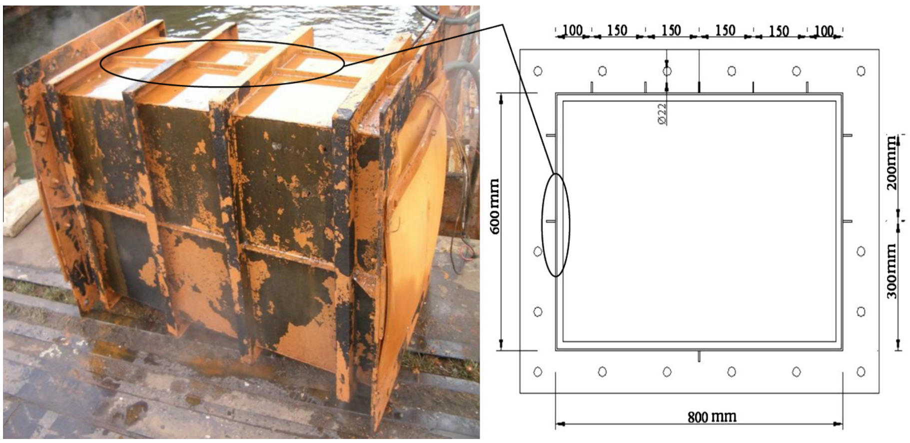

Fig. 1. Box girder after the test in hot sea water with anodic polarization [32].