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Abstract

Offshore structures are faced to aggressive environmental conditions (sea salt, bio-colonization), and to high mechanical fatigue due to cyclic wave loading. Because of these conditions, their maintenance plays a key role in their reliability over time. The use of monitoring in such a case could allow drastic decrease of maintenance costs provided safe and reliable systems may be applied on site. The presented work introduces our laboratory investigations concerning different electrochemical and nondestructive techniques used to monitor these damage mechanisms. Firstly, accelerated corrosion tests by artificial tidal cycles with natural seawater are described. They are carried out on carbon steel coupons with and without protective coating in order to monitor the evolution of corrosion versus time. Several parameters are measured during the test such as corrosion intensity, pH, corrosion potential and environmental parameters (temperature, seawater salinity). Secondly, fatigue sensors and more classical strain gauges have been used during mechanical fatigue tests to monitor damage under normalized fatigue cycles. The tests were carried out on T welded joints until failure. For each case, the comparison of the different techniques allows concluding on their suitability. Further investigations in laboratory are currently done to ensure such a conclusion, especially on durability issue. The final validation of these techniques will then be done on site with the help of a reduced-scale prototype at sea near French Atlantic coast.

Keywords: condition monitoring, offshore, health monitoring, corrosion, mechanical fatigue, reliability, offshore structure

1. INTRODUCTION

Offshore steel structures are faced to extreme service loads and aggressive environments. The safety of these structures may be affected by different damages among which corrosion and fatigue are the most prone to occur. In this context, IFSTTAR is currently working with several partners in a project called SURFFEOL (Survey and reliability of offshore wind turbines jackets) in order to give such solutions to offshore wind farms developers. One of the main objectives of this project is to carry out health monitoring of a wind turbine steel foundation to determine damage factors in relation with corrosion and fatigue damages. As inspection operations are particularly difficult to carry out in such environment, many non-destructive techniques have been investigated by various researchers to monitor corrosion and fatigue under offshore conditions [1]. In previous studies, the authors have precisely identified the locations where the risks of degradation were the highest and listed
the available monitoring techniques for both corrosion and fatigue [2, 3, 4]. Some of these sensors are now being assessed in laboratory conditions to study their adequacy with the studied phenomena and their reliability. Corrosion and fatigue phenomena can be monitored with different types of sensors such as acoustic emission techniques [4, 5], ultrasonic methods [6, 7], optical fibers techniques [4, 8], thermal imaging methods [9, 10], and others. Specific sensors for corrosion monitoring such as coupled multielectrode sensors are also reported [11].

In order to assess the suitability of corrosion devoted sensors, an artificial tidal cyclic test with natural seawater, which simulates marine environment, has been set up. In parallel, fatigue tests have being carried out with different sensors. The first part will present thoroughly the led experimental investigations, regarding the studied materials, the corrosion process and related monitoring strategy, and the fatigue investigations with tested sensors. The second part will present the first obtained results, the investigations being still in progress.

2. EXPERIMENTAL METHODS

2.1 Materials

Laboratory investigations were conducted on S355G8+M carbon steel. According to standard NF EN 10225 [12], S355G8+M is a thermo-mechanically rolled structural grade steel used in offshore industry for the construction of fixed offshore structures. Two specimen dimensions were used: 100x100x8 mm$^3$ coupons for accelerated corrosion tests and T-welded joint samples for fatigue tests.

Corrosion tests were carried out on 3 type of samples tested in artificial tidal and immersion conditions using natural seawater: i) as-received steel coupons, ii) coupons with protective coatings and iii) coupons with the same protective coating including a defect (based on the recommendation of ASTM G8 [13]). The offshore coatings under investigation are three-component coating for tidal zone and two-component coating for immersion condition. The first system is made of Hempadur Multi-strength and Hempathane with a 830 µm total average thickness and the second of Hempadur Multi-strength with a 500 µm total average thickness.

A carbon steel rod was fixed and isolated on each coupon to allow a secured connection between coupons and electrochemical instruments. Natural seawater was used and stored in closed tank during 2 months to let the solid particles settle to the tank bottom. Before tests, seawater was filtered with a glass microfiber filter.

Ten similar T-welded assemblies were realized with classical methods used in offshore steel construction. The fatigue class of such details is considered to be G according to BS specifications [14] and F according to DNV specifications [15].

2.2 Accelerated corrosion test and corrosion monitoring

The accelerated corrosion test was carried out by exposure of samples to two saline environment conditions: i) to an artificial tidal condition and ii) to an immersed condition in natural seawater. Coupons in the tidal zone were subjected to alternate conditions for 2h immersion in natural seawater and 2h drying at room temperature and relative humidity. The electrolyte solution was introduced into the vessel from an external storage tank through the inflow-pumping valve specifically programmed for our experiments. Coupons were
immersed in seawater for 2 h and then seawater was drained through the outflow-pumping valve allowing samples to dry during 2 h at room temperature and relative humidity. Coupons in the immersed zone were subjected to immersion in seawater throughout the experiment duration. The experimental setup is described in Figure 1.

During one month of artificial tidal cycles on coupons, the corrosion potential was monitored with a data logger EPC8 from NKE. Data logger EPC8 consists in measuring the corrosion potential between a coupon and a reference electrode every 1 minute. It contains 8 independent measuring channels; it is autonomous and designed to be installed in a humid marine environment. Additional measurements such as the corrosion potential, the polarization resistance $R_p$ using a potentiostat (VSP Bio-Logic) were performed to support the corrosion potential measurements from data logger EPC8. The corrosion current density is used instead of $R_p$; it is calculated from $R_p$ values by using Stern-Geary equation [16]. A three-electrode cell configuration was employed for polarization measurement with a saturated calomel reference electrode (SCE) and a 316 L steel grid counter electrode.

![Figure 1: Experimental setup for the accelerated corrosion test](image)

### 2.3 Fatigue test and monitoring

In order to assess the suitability of different monitoring devices, it was decided to realize 10 fatigue tests: 6 tests would be carried out at constant stress amplitude but for two different stress ratios $R$ (corresponding to the minimum applied stress divided by the maximum applied stress), 3 tests would be carried out at varying stress amplitude, and 1 test would be dedicated to a preliminary study of durability of the proposed system. We will only present here first investigations related to tests at constant amplitude and for a stress ratio of 0.1 corresponding to the value adopted for the definition of fatigue classes in [14, 15]. The investigations were done at a frequency of 7Hz and for stress amplitudes of 110 MPa and 140 MPa.

Fatigue phenomenon is associated to three main steps [17]: cracking initiation, cracking propagation, and failure. Most of existing inspection or monitoring strategies are therefore associated to the ability of crack detection within steel elements [18]. As cracks were not accepted to occur in our application, our study focused on monitoring strategies adapted before cracking propagation has started. It is interesting to note in that case, that there is no clear evidence of the level of damage of the structure. The level may only be assessed through indication on the load history of the structure or the element.
Amongst the tested sensors, we will only present here the results given by six resistive strain gauges that were bonded at 15 mm of the weld toe (corresponding to a classical method of measurement) and by two Crackfirst™ sensors (provided by Strainstall UK) that were welded on each side of the reinforcement [19] but on the other side of the plate. The sensors location is shown on Figure 2. Ultrasonic inspection was also punctually carried out during the experiments to detect crack initiation and propagation.

![Figure 2: Experimental setup of T welded joint plate for the fatigue test and location of sensors](image)

3. RESULTS AND DISCUSSION

3.1 Potential corrosion monitoring

Laboratory potential measurements were achieved in order to validate techniques that will be used on site. Potential ($E_{\text{corr}}$) and current density ($i_{\text{corr}}$) against time obtained for 2 samples in tidal zone and 3 samples in immersion zone are presented in Figure 3 and Figure 4 respectively. The calculation of $i_{\text{corr}}$ is given only for the active surface of samples in contact with the solution. In the case of coated coupons, the coating breakdown factor is taken into account according to the recommended practice DNV-RP-B401 [20]. One month of measurements is shown for the two environmental conditions. During test, pH, salinity and temperature of seawater were determined in the range of 8.1–8.5, 29.5 - 31 g/l and 18.5-20°C respectively.

It is important to note that the corrosion potential monitored by data logger EPC8 was continuously measured, even when coupons were not immersed in seawater (i.e. for coupons in tidal zone). Measurements with the potentiostat were performed only during the immersion of all samples in seawater.

For samples undergoing tidal cycles, $E_{\text{corr}}$ varies with tide between -0.70 V/SCE and -1.4 V/SCE (lowest values) for A1 sample (Figure 3). This variation of $E_{\text{corr}}$ is between -0.61 V/SCE and -1.4 V/SCE (lowest values) for A2 sample (Figure 3). The strongest values of $E_{\text{corr}}$ correspond to the immersion period and are supported by values obtained from the potentiostat. The corrosion potential decreases rapidly when coupons emerge from seawater as shown by Refait et al. [21] on unprotected steel coupons. These variations are difficult to explain because of the surface state of samples. Indeed, the imbibition/drying cycles and temperature variations on the surface sample can have an influence on the measured values. For A1 sample, $E_{\text{corr}}$ increases slightly from -0.72 to -0.68 V/SCE during the immersion period. This evolution is consistent with $i_{\text{corr}}$ decreasing from 3.1 to 0.3 μA.cm$^{-2}$ that can be explained by the formation of corrosion products on surface sample which can be considered
Figure 3: Corrosion potential and current density vs. time for uncoated steel coupon (A1), coupon with protective coating including a default (A2) under tidal conditions, and zoom on A2 for time interval between 100-150h
Figure 4: Corrosion potential and current density vs. time for uncoated steel coupon (B1), coupon with protective coating including a defect (B2) and coupon with intact protective coating (B3) under immersion conditions.

as a protection against corrosion. For A2 sample, $E_{\text{corr}}$ and $i_{\text{corr}}$ remain almost constant during all test duration at -0.61 V/SCE and 0.8 µA.cm$^{-2}$ respectively. For samples in immersion zone, $E_{\text{corr}}$ provided by data logger EPC8 is more stable (Figure 4) and is consistent with values from the potentiostat. The $E_{\text{corr}}$ of unprotected coupon (B1) tends to increase slightly with time from -0.77 to -0.75 V/SCE. These data are in adequacy with the decrease of $i_{\text{corr}}$ from 4.7 to 0.9 µA.cm$^{-2}$ and the formation of corrosion products on surface coupon. The $E_{\text{corr}}$
of B2 and B3 samples fluctuates slightly around -0.71 V/SCE and -0.69 V/SCE respectively. The $i_{corr}$ varies between 0.23 - 1.7 $\mu$A.cm$^{-2}$ and 0.05-0. 22 $\mu$A.cm$^{-2}$ for B2 and B3 respectively. The difference between these two samples is the presence of defect that increases $i_{corr}$ of B2 sample. The $i_{corr}$ values of B2 are in the range of these of B1 coupon that can be explain by a corrosion concentration on the defect as observed for the crevice corrosion phenomenon.

In conclusion, the monitoring of the potential with data logger EPC8 gives indications on the evolution of corrosion versus time; data are consistent with those obtained with the potentiostat. These data are also supported by $i_{corr}$ values. Further investigations in laboratory are currently done under cathodic protection (by sacrificial anode and imposed current) to ensure such a conclusion. The final validation of this technique will then be applied on a reduced-scale prototype placed on site.

### 3.2 Fatigue damage assessment

The most common method to determine fatigue assessment on existing structure before cracking propagation relies on strain gage monitoring [18]. This strategy consists in recording the local strain variations and post-analyzing them in order to identify the stress ranges, the mean stress values, and the number of cycles for each. To this aim, the most widely used method is the Rainflow method [22]. Miner’s Rule can then be used to assess the final damage based on existing fatigue assessment on similar details [23]. Such method therefore requires a rather high amount of recorded data and of electric supply as rather high frequencies of sampling are used.

A novel method developed by Strainstall UK, Crackfirst™ sensor, consists in the fixation of a pre-cracked patch on the structure and on the monitoring of the rate of increase of the crack length of this patch. The method requires a precise calibration in laboratory that has been led with the help of The Welding Institute (TWI) [24]. The crack propagation is followed through the failure of electrical links on both sides of the crack (Figure 5). One sensor gives therefore two measures of the length of the patch crack that may be related with the fatigue damage of the structure through the existing calibration. The advantage of such a sensor is that it requires much less energy as there is no required post-treatment and as it may be interrogated at any time. The amount of data is also much less important as the only information is the occurrence of failure of the electric wires. Of course, it has also some drawbacks, the main one being that it is impossible to get access to data concerning strain history of the studied detail.

![Figure 5: Photo of a Crackfirst sensor](image)

Though, the investigations are still in progress, first results are presented in Figure 6 for the sample stressed at an amplitude of 110 MPa (this sample was then stressed at 140 MPa to increase the damage rate) and 140 MPa at a ratio of 0.1. It can be stated that the results of
Crackfirst sensor for that case are in close agreement with the expectations. The sensor even seems to give conservative indications close to the total design life. Such sensor may thus offer a reliable alternative to the commonly adopted strain measurement methodology that requires important supply and amount of data to be recorded. For all the tests that were carried out, the number of cycles for crack initiation determined from ultrasonic investigations and the total number of cycles at failure are reported in Table 1. This allows from the DNV specifications [15] and the Miner’s rule [23] the determinations of the fatigue degrees of damage at crack initiation and at failure. It can be observed that recommendations are very conservative for our case, as the determined fatigue damage degrees are above 2.5 for crack initiation.

**Table 1:** Determination of the degree of fatigue damage for the realized investigations

<table>
<thead>
<tr>
<th>Sample</th>
<th>Crack detection (US)</th>
<th>Crack detection (US)</th>
<th>Crack detection (US)</th>
<th>Crack detection (US)</th>
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<td>190000</td>
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<td></td>
<td>1339430</td>
<td>261000</td>
<td>2,8</td>
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</tbody>
</table>

4. CONCLUSIONS

In this study, two experimental approaches were used to assess the suitability of corrosion and fatigue sensors chosen to monitor the evolution of corrosion and fatigue on site. Potential data obtained with data logger EPC8 and the potentiostat are similar and consistent with the evolution of the current density. Data logger EPC8 allows to monitor the corrosion potential and give qualitative information on corrosion. Design fatigue life obtained for Crackfirst sensors is in adequacy with the DNV specifications [15]. Crackfirst sensor can give some
indications on the total design life of structure; it offers a good alternative to the classical
strain measurement methodology.
Further investigations are in progress to validate the choice of these sensors to study both
damaging phenomena. The final validation of these techniques will then be applied on a
reduced-scale prototype placed on site near French Atlantic coast.

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