Proceedings IRF2018: 6th International Conference Integrity-Reliability-Failure
Lisbon/Portugal 22-26 July 2018. Editors J.F. Silva Gomes and S.A. Meguid
Publ. INEGI/FEUP (2018); ISBN: 978-989-20-8313-1

PAPER REF: 7166

THE EFFECT OF FRESH WATER CORROSIVE SOLUTION ON FATIGUE STRENGTH OF LOW CARBON STEEL

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ABSTRACT

This paper investigates the effect of corrosive environment on fatigue strength of circular cross section specimens made from structural low carbon steel. Extensive experimental programme has been conducted to understand how the fatigue strength of S355 steel is reduced by both fresh water environment and artificial sea water environment and how positive mean stress affects the corrosion fatigue life of specimens. Moreover, two circuits, designed to allow the circulation of corrosive solution during the application of cycling load, are proposed and the effect of corrosive flow conditions on the surface of specimens related with the two designs are discussed and quantified.

Keywords: corrosion fatigue, corrosive environment, mean stress.

INTRODUCTION

Corrosion fatigue failure is a fundamental design consideration in many industrial fields, especially for mining industry, where pump components work under the influence of alternating loading caused by cyclic pressure in corrosive environment that attacks and degrades material surface quality. Components made of low carbon steel are attractive in design due to general material properties and relatively low cost but have a disadvantage of low resistance to corrosion fatigue.

Many studies have been developed to understand how corrosive environments affect fatigue life of steel [6] and how the strength of material decreases. Usually, artificial sea water conditions are tested and many data are available in literature [2, 3, 8] that describe this condition. However, different kinds of corrosive environment are less popular in research and, consequently, less data are available. In this study, because of the industrial requirements, a fresh water solution is mainly used in the development of testing. Moreover, few fatigue tests were performed also in air and in $3.5\% NaCl$ corrosive aqueous solution.

Many test rigs have been proposed in literature to carry out corrosion fatigue testing. [4, 5, 9]. Depending on the application, specimens can be or initially pre-corroded and later stressed with cycling load or corroded during the application of cycling load (in-situ corrosion). When the corrosion is in-situ, specimens can be totally immersed in the solution using sealed chamber or corroded under a flow in an open chamber. In this work two different test rigs are proposed and used for corrosion fatigue tests, both of them allow corrosion in situ and chamber is sealed to the specimen during the test.

EXPERIMENTAL PROCEDURE

Material used for this work is low carbon forged steel S355J2G3+N. Chemical composition, mechanical properties and design of samples have already been described in [7]. Both tests in air and in corrosive environment were carried out using 6 mm diameter specimens designed according to ASTM E466-07 [1]. The roughness of the gauge length surface of each specimen was evaluated through the arithmetic mean of four different measurements. Value were between Ra=0.095 micron and Ra=0.130 micron.

Four sets of fatigue tests are proposed in this work:

- Fatigue tests in air at room temperature;
- Fatigue tests in fresh water corrosive environment $[824\,ppm NaCl]$ using corrosion cell Configuration 1;
- Fatigue tests in artificial sea water corrosive environment $[3.5\% NaCl]$ using corrosion cell Configuration 1;
- Fatigue tests in fresh water corrosive environment $[824\,ppm NaCl]$ using corrosion cell Configuration 2.

Fatigue tests in air were performed under axial loading and load controlled with servo hydraulic fatigue testing system - Instron 8801 and Instron 8802 - at a fixed frequency of 15 Hz. Two conditions of stress ratio, R, were tested in air: a fully reversed loading R=-1, and positive mean stress R=0.

In order to reproduce the simultaneous effect of fatigue and corrosion phenomena, a corrosion cell was designed, developed and produced at the laboratory AMRL, compatible with the servo-hydraulic machine. This cell, in-built to the specimen, allows the continuous flow of the corrosive solution during the application of cycling load and, consequently, the corrosion of the central part of the specimen. The cell is designed to encase the central part of specimen and leave its grip parts free. To ensure the sealing of the chamber, two seals made with Black Tango™ are used. The inlet and outlet holes created in the cell for circulation of solution are placed in the top part of the cell, one in the left side of specimen and the other one in the right and diameter dimension of holes is 9 mm. To create the circulation of solution during the test, a plastic pipe was connected to the inlet of cell and, from the other side, to a water pump of nominal flow of 600 l/h placed in a tank. From the outlet the corrosive solution was returned in the tank through the same dimension plastic pipe. An air pump of nominal capability of 100 l/h was located in the tank to oxygenate the water during the test. A schematic circuit is illustrated in Figure 1.

This cell configuration, characterized by inlet and outlet placed in the top part of the cell, has been denominated Configuration 1. It is used to performed corrosion fatigue tests in AMRL laboratory for both fresh water corrosive environment and artificial sea water environment. All these tests were performed at 10 Hz, using either servo-hydraulic fatigue testing system Instron 8801 and Instron 8802.

Three stress ratio configurations were carried out for corrosion fatigue tests in fresh water environment: fully reversed loading R= -1, positive mean stress R=0 and positive mean stress R=0.5.

Tests in artificial sea corrosive environment were performed at stress ratio R=0.

A set of tests presented in this research work were performed in a laboratory outside the University, by EXOVA Group. Material, specimen geometry and dimensions are exactly the same of specimens used in AMRL laboratory. The general idea behind the circuit developed to allow corrosion during fatigue test is similar to the one used in AMRL laboratory. In fact the solution was aerated using an air pump and its circulation was allowed by a peristaltic pump placed in the tank and connected to the inlet of the cell. The main different between the two circuits is the geometry of cell: in fact, in the configuration used in EXOVA the inlet and outlet diameter is 6.35 mm (1/4 inch). Moreover, inlet hole is placed in the bottom part of the cell and outlet in its top part, from the same side of the samples. This configuration, characterized by inlet and outlet placed in the same side of the sample, is denominated Configuration 2 and it is used for tests in fresh water environment run in EXOVA. A schematic illustration of this circuit is shown in Figure 2.

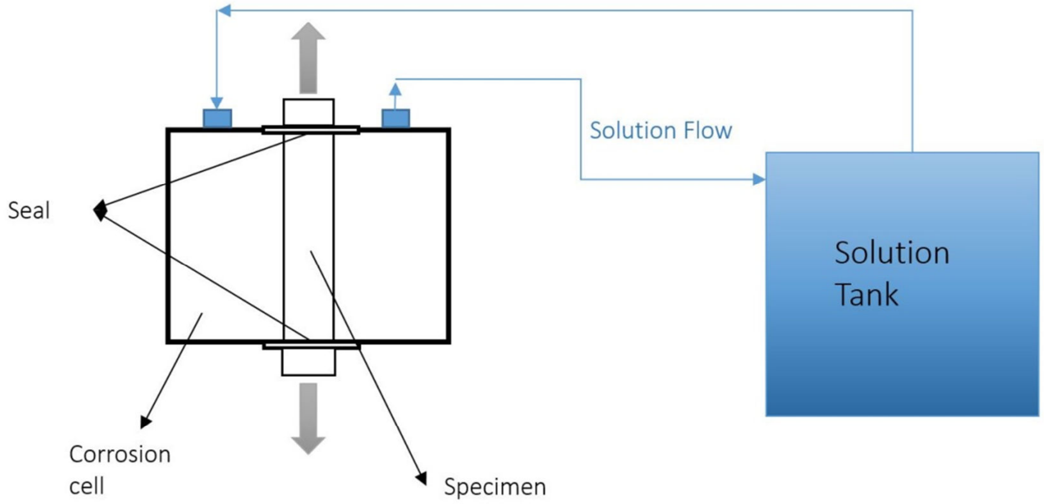

Fig. 1 - Circuit used in Configuration 1

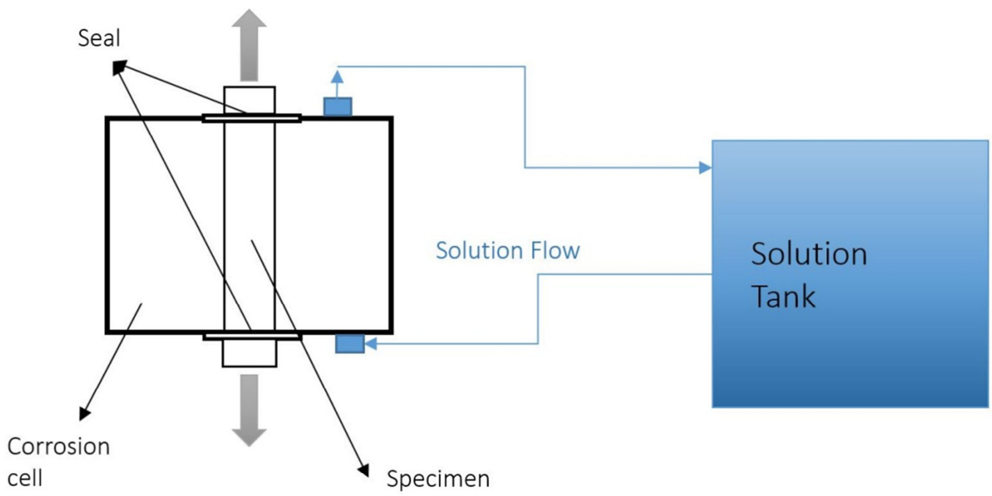

Fig. 2 - Circuit used in Configuration 2

Characteristics of aqueous corrosive solution for the three sets are reported in Table 1.

Table 1 - Characteristics of aqueous solution environments

Salinity [% NaCl]	Conductivity [mS]	Temperature [°C]	pH	Flow [l/h]	Configuration Cell
0.0824	2.0 ±0.2	25 ±1	6.9±0.1	190	1
3.5		25.5+1	7.0±0.1	190	1
0.0824	2.0±0.3	25±1	7.5±1	100	2

EXPERIMENTAL RESULTS

Experimental results obtained from fatigue tests in air conducted at room temperature, both for stress ratio R=-1 and R=0, are plotted in a log-log scale diagram and shown in Figure 3.

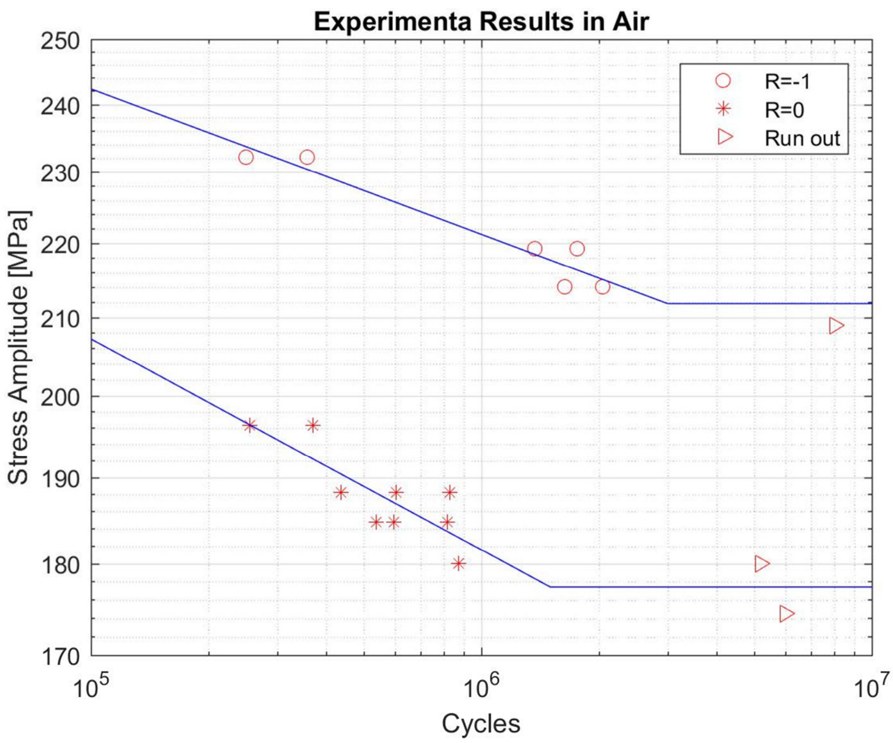

Fig. 3 - Results in Air

Results in air show the typical behaviour of steel in fatigue life: in fact, it is possible to express data trends using Basquin's law, up to 2x10^6 number of cycles, where the slope of the trend change because of a possible fatigue limit:

$$\sigma_A = a \times N^b \tag{1}$$

Moreover, it is possible to notice that, under positive mean stress (R=0), fatigue strength decreases and the change of slope appears at lower number of cycles.

These data obtained in air are considered as reference to evaluate the effects of corrosive environment.

Experimental results obtained from corrosion fatigue tests in fresh water environment with Configuration 1 of corrosion cell are plotted in a log-log diagram and S-N curves obtained from interpolation of experimental data are shown in Figure 4. Interpolation of data for all the three S-N curves, characterized by different stress ratio, can be expressed, as in fatigue in air, by Basquin's power law equation (1). In this case, the slope of the line is constant through all the region taken into account (10^5 to 10^7), therefore the equation can be employed, at least, till $10^{7.}$ In other word, in this region, the fatigue limit in corrosive environment doesn't occur.

S-N curves show a reduction in fatigue strength with increasing positive mean stress. In fact, at 10^6 number of cycles for R=0 the reduction of strength is 23% compared to the fully reversed data and 33% for R=0.5. This trend is not constant with the number of cycles, in particular for R=0.5 that at 10^7 cycles shows a reduction of 38% compared to S-N curve obtained at the fully reversed loading.

A comparison between the behaviour of carbon steel under fatigue in air and in fresh water environment is shown in Figure 5. In the region between 10^5 and $5x10^5$ the effect of corrosive environment on fatigue strength is relatively low: this is due to corrosion time depending. Since tests were carried out at 10 Hz, to achieve 10^5 cycles the sample were corroded for less than 4 hours during the effect of fatigue loading. In this amount of time corrosion started on the surface of sample but, obviously, didn't affect too much the surface of sample and therefore the fatigue strength. At higher number of cycles the effect of corrosion on fatigue life is more intense. At $10^{\ 7}$ number of cycles fatigue strength in fresh water is reduced by a factor of 2.1 compared to results in air.

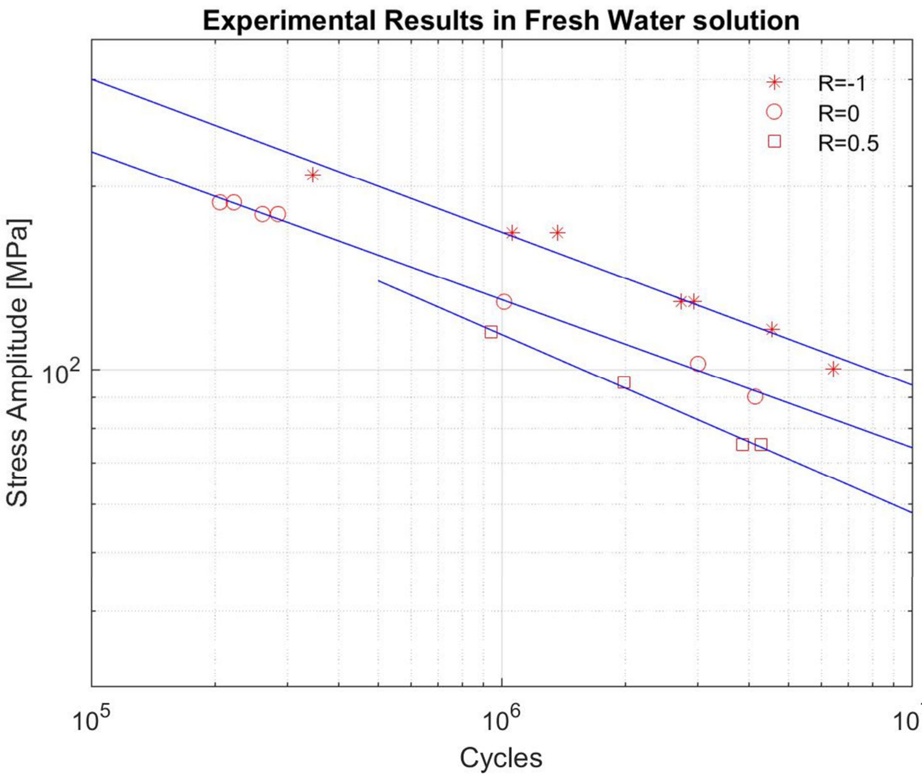

Fig. 4 - Comparison air and fresh water fatigue results

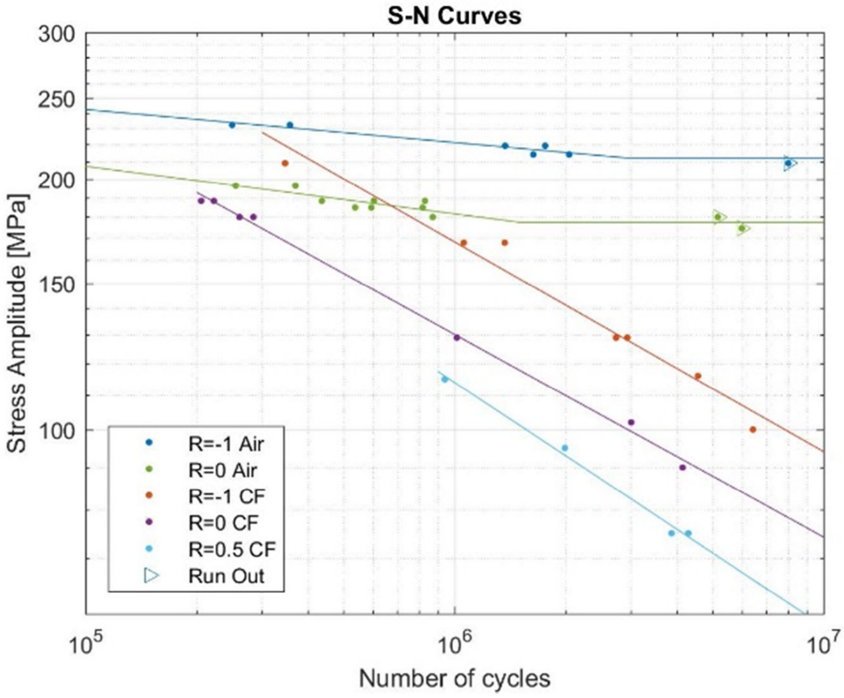

Fig. 5 - log-log SN curve in fresh water

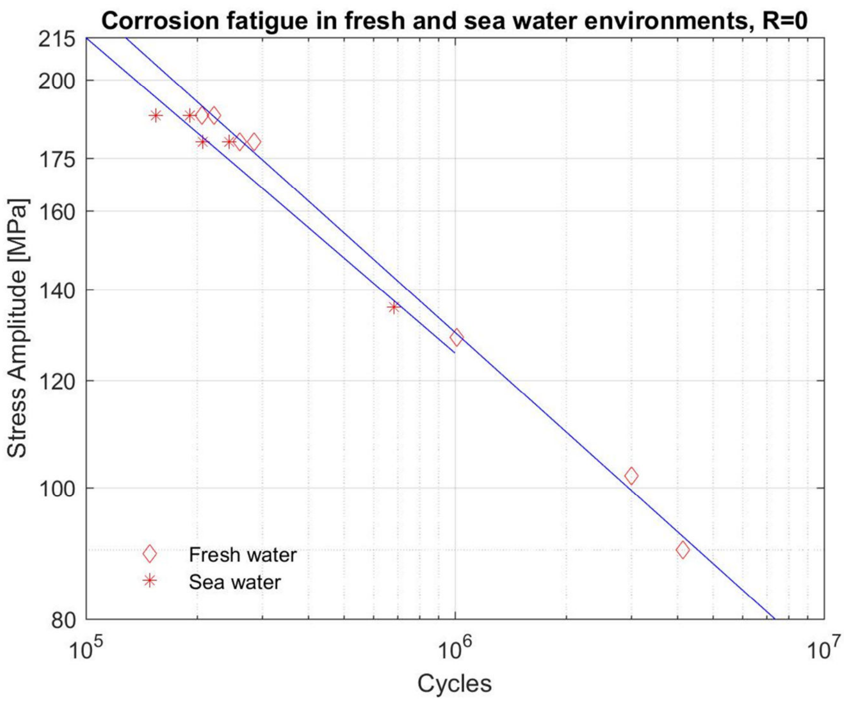

Fig. 6 - S-N curves in fresh and salt water corrosive environment

Experimental results obtained from fatigue tests in artificial sea water corrosive environment are plotted in a logarithmic scale in comparison with results obtained in fresh water environment for stress ratio R=0. S-N curves obtained from the interpolation of experimental data are shown in Figure 6. In artificial sea water environment, tests were carried out at relatively low number of cycles (< 10^6) and consequently the effect of corrosive environment on sample surface was pretty limited. Although duration of tests was maximum 16 hours ($6x10^5$ number of cycles), it is possible to see that corrosion fatigue life is already affected by the more corrosive solution and fatigue strength drops.

Experimental results obtained from tests run in EXOVA facility using corrosion cell Configuration 2 are plotted in a log-log graph and compared with results obtained using corrosion cell Configuration 1. Experimental data and S-N curves obtained from the interpolation of those points are reported in Figure 7.

As described in the previous part, the only difference between these two sets of data is the circuit used to create the circulation of solution during the test. Since in Configuration 2 the inlet and outlet on the cell are placed in the same side, it has been found that the corrosion on surface has affected mainly that side of the sample instead being uniformly on all its surface, as observed in samples tested with cell Configuration 1. The effect of corrosion surface distribution on fatigue life is significant especially in the region of higher number of cycles. In fact at 75 MPa of stress amplitude, the difference in number of cycles between the two sets is more than 5 million of cycles.

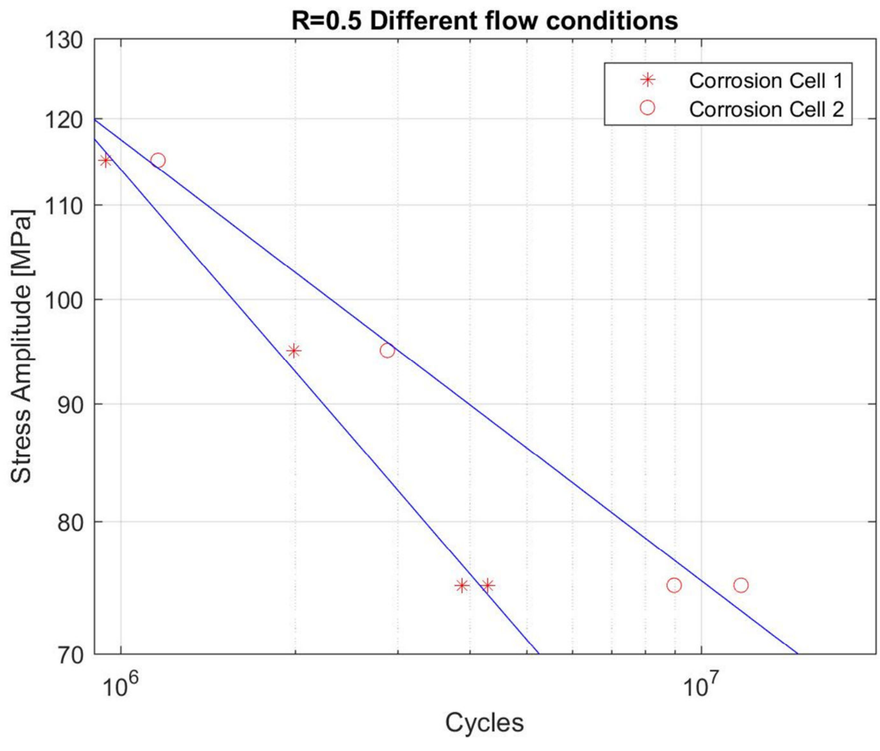

Fig. 7 - Comparison between results obtained with different corrosion cell

CONCLUSION

This study presents the experimental results of effect of fresh water and artificial water on the fatigue strength of low carbon steel and the effect of corrosive solution flow on the fatigue life.

Experimental results show that the effect of fresh water environment on fatigue strength is to reduce the fatigue strength of material: the degradation is higher at lower level of stress but occurs even at lower number of cycles. At 10^7 number of cycles fatigue strength is reduced by a factor of 2.1. A fatigue limit is not observed in the region from 10^5 to 10^7 number of cycles. A reduction if fatigue strength occurs also with positive mean stress in corrosive environment.

A comparison between corrosion fatigue data in fresh water solution and artificial sea water solution show an additional reduction in fatigue strength due to the more corrosive environment. This degradation of strength occurs after even at really limited number of cycles.

Finally a comparison between two test rigs cell is studied: experimental results show a significant increase in number of cycles in relation with a linear flow distribution inside the cell and a lower flow rate. These parameters affects the corrosion distribution and intensity on sample surface and consequently on its fatigue life. This effect is more intense at higher number of cycles.

ACKNOWLEDGMENTS

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Currie grant agreement No 643159.

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